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Cover: Adélie penguins. (H. Armstrong Roberts)

Southern Ocean Exploration

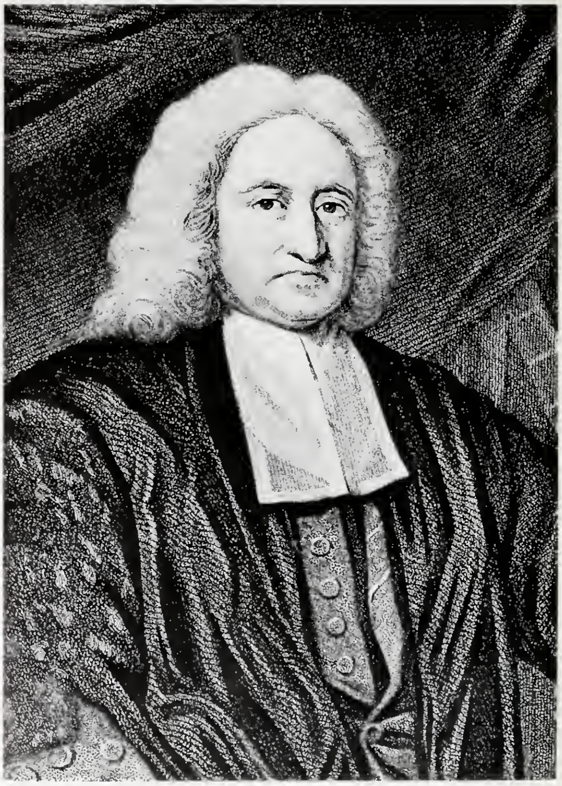
Sir George Deacon

Our knowledge of the Southern Ocean begins with the early explorers who were expected to record information on navigation and be ready to extend their interests when the occasion arose. Edmund Halley, discoverer of the comet in 1682, led the first scientific expedition to the area in 1700. His instructions from the British Admiralty were to call at as many islands as possible, to measure magnetic declination, and to explore the coast of *Terra Incognita,* supposed to lie between the Straits of Magellan and the Cape of Good Hope. He was stopped by ice at 52½°S in the east Atlantic Ocean. A year later Halley published a map showing the magnetic variation.

Captain James Cook was no stranger to scientists. Sir Joseph Banks, an eminent natural historian, sailed on Cook's first voyage (1768-71) and contributed a lot to the results and the public appreciation of the venture. Two astronomers, William Wales and William Bayly from Greenwich Observatory, sailed on the second voyage (1772-75) and showed that there was warmer water below the cold antarctic surface layer. And though the Forsters, the German father and son recruited for the second voyage, caused enough trouble to prejudice Cook against taking any more naturalists to sea, it soon became common practice. The Russian admiral Thaddeus Bellingshausen, who circumnavigated the Southern Ocean in 1819-21, expressed regret at having to sail without a naturalist and towed a net himself.

Sealers and whalers attracted to South Georgia by Cook's accounts made numerous contributions to Southern Ocean research. In 1821 George Powell, an English sealer, again found the warm layer below cold surface water and noted that similar conditions had been found to exist in the Arctic. In 1823 James Weddell, another English sealer, sailed in open water as far as 74°15'S, measuring temperatures until his thermometers were broken. James Eights of Albany, who in 1829 sailed with the American captains Palmer and Pendleton to the sealing grounds, described the natural history of the South Shetland Islands and discovered a new crustacean and marine spider. He also recognized the ability of icebergs to carry rock fragments far from their source.

The national expeditions to the area—led by Dumont d'Urville of France (1837-40), Charles Wilkes of the United States (1838-42), and Sir James Clark Ross of Britain (1839-43)—sailed with formal scientific programs, including



Edmund Halley, English astronomer and mathematician, led the first scientific expedition to the Antarctic in 1700. (Bettmann Archive)

Harpooning a whale, ca. 1840. Some of the early whaling and sealing voyages contributed to Southern Ocean research. (Bettmann Archive)

deep temperature measurements, biological collecting, and research in geology, magnetism, tides, and meteorology. Notes of navigational importance were also made. Temperature measurements on these voyages, however, were less useful than they might have been. Thermometers were not protected against pressure, and the high readings that ensued convinced scientists on board that the bottom water must have a temperature of 4°C; yet several years prior to the expeditions, Georg Friedrich Parrot and Emil Lenz had published a careful study of the effect of pressure on thermometers. Similarly, the opinion persisted that sea water was like fresh water in having a maximum density above its freezing point; this, despite the work of Alexander Marcet, a Swiss doctor working in London, who showed in 1819 that this was not the case. It seems reasonable to suppose that some of the unawareness of past work was due to the physical studies (as distinct from biological and geological work) being left to professional sailors for whom they were necessarily a secondary activity.

To write a historical account of the advance of biological knowledge of the Southern Ocean is quite a difficult task and one that might well prove rewarding for an expert who knows his way about biological collections. Some of Ross's material was not adequately preserved, but Richardson, Inspector of British Naval hospitals and very much a surgeon naturalist, was able to describe 234 fishes, of which 145 were new to science. Wilkes may have had a still larger collection of fishes. Louis Agassiz, the Harvard professor who advised the Coast Survey, did much work on Wilkes's collection, but his manuscript and drawings were not published, and only a little of the original material has been described. There were important publications on botany and zoology by J. D. Hooker, who sailed with Ross; Dana, geologist on the Wilkes expedition; and others—but it seems that the work was not completed.

Scientists aboard *Challenger*, the British

(Top) Charles Wilkes, American explorer and naval commander. (Bottom) Men from Wilkes's expedition take turns working on the ice. (Bettmann Archive)

research vessel whose four-year (1872–76) cruise around the world marked the beginning of sustained deep-sea research, went to great pains to preserve and describe their collections. In fact, *Challenger*'s scientific director, Wyville Thompson, and his successor, John Murray, ran into a lot of financial and other trouble because of their determination to have each group of animals worked on by the best man they could find, no matter where he lived. Nevertheless, they completed the work and rounded it off with a two-volume summary of results. The fact that publication of the full report took twenty years brought adverse comment, but we take even longer nowadays. The reports of the German South Polar Expedition of 1901–03 were still being published up to 1926, and the latest report of the Swedish Antarctic Expedition (1901–03) appeared in 1959. In any event, there evidently was some effort at economizing during publication of the *Challenger* report: most copies of Volume 31 contain a printed slip saying that the volume itself was recovered from the sea; a consignment of the volume was shipwrecked on the way from Edinburgh to London but rescued, dried out, given new plates and the printed apology, and sold—water stains and all.

There was a great revival of antarctic exploration at the end of the nineteenth century. *Antarctic*, a former whaler, was the first ship to enter the Ross Sea since Ross discovered it in 1841.

Two of her complement, H. J. Bull and C. E. Borchgrevink, young Norwegians who had worked in Australia, were the first to land on the continent—at Cape Adare. Borchgrevink returned there in *Southern Cross* (1899-1900) and was one of the first party to winter ashore in the Antarctic, in 1899. Hanson, the Norwegian biologist on the expedition, was the first to be buried on the Antarctic continent. His notes on the seals were prepared for publication in the 344-page report on the expedition by Dr. Edward Wilson, who died with Captain Robert F. Scott in 1912.

The Belgian *Belgica* expedition wintered at sea in 1898, drifting in the pack-ice of the Bellingshausen Sea. Her party was able to make a continuous series of observations during the 12 months of entrapment, and their reports were published in 1901-38. The Swedish Antarctic Expedition followed soon after in the ship *Antarctic,* which had been to the Ross Sea in 1895. She was crushed in the ice in 1903, and while three separate Swedish parties were wintering at Hope Bay, Snow Island, and Paulet Island—within about 50 miles of each other near the northern end of the Antarctic Peninsula—W. S. Bruce (formerly doctor and naturalist with a whaling expedition from Dundee in 1892) and his Scottish Antarctic Expedition (1902-04) were wintering aboard *Scotia* in Scotia Bay in the South Orkney Islands, not far to the eastward. (*Scotia,* well equipped for sounding and bottom-trawling, made extensive collections in the eastern half of the Weddell Sea.)

Money for publication of observations and findings was a continual problem. The extensive biological and geological results of Captain Scott's two polar expeditions were published by the Trustees of the British Museum; the physical results of the first expedition, by the Royal Society. However, the physical results of the second expedition were put out by a publications committee using part of the money raised by public subscription for a memorial to Scott and for helping the dependents of those who died with him. The English explorer Sir Ernest Shackleton's expedition of 1907-09 had to raise money itself for all its publications, covering coastal and fresh water biology, botany, and geology. And, in 1918, Bruce complained he could only raise sufficient funds to complete six of the twelve volumes needed by his expedition (though many of his papers appeared in the Transactions of the Royal Society of Edinburgh). In general, the reporting of biology and geology were better provided for than were the newer sciences.

Belgica, Antarctica, the German expedition in *Gauss* (1901-03), and the French expeditions in *Français* (1903-05) and *Pourquoi Pas?* (1908-10) included physical oceanography in their programs—work showing that warm water pushes south between the cold surface and the bottom layers as far as the continental slope, sometimes sending weak thrusts into the colder shelf seas. Dr. Meinardus, meteorologist in the German South Polar Expedition in *Gauss,* was the first to describe, in 1921, the abrupt sinking of "ice water" below warmer water along the line now called the Antarctic Convergence (see page 11). Surface and bottom temperatures and densities, and a few vertical series, were published in the *Scotia* Station Log in 1918.

Land-based expeditions had less opportunity to work at sea, but observations that have recently come to light—made during the winters of 1911 and 1912 by Nelson, biologist at Scott's winter quarters—give a good idea of seasonal changes in temperature and show the high salinities due to winter freezing noted by later studies. *Fram,* which carried Roald Amundsen to the Antarctic, apparently made no observations in the Southern Ocean; but while the Norwegian explorer was wintering at the Bay of Whales, she worked two sections across the South Atlantic Ocean, between 15° and 30°S, mostly down to 1000 meters. In September 1911, she was lying in Buenos Aires at the same pier as the German vessel *Deutschland,* on her way south with Wilhelm Filchner's Weddell Sea expedition. During this expedition, Professor Brennecke of Hamburg, using protected and unprotected reversing thermometers and the Knudsen titration, contributed more than anyone so far to knowledge of structure and movements in the Antarctic Ocean. His brief report, sent home from Buenos Aires in 1911, showed that North Atlantic deep water exerts a large influence in the South Atlantic; his final report, published in 1921, recognized that warm deep-water flows westward into the southern half of the Weddell Sea from the Indian Ocean and gave a sound explanation of the formation of Antarctic Bottom Water (see page 12). His findings clearly stimulated further advances in Germany and must have helped to promote her *Meteor* expedition (1925-27), which greatly extended our knowledge.

The *Discovery* investigations, which began in 1925 with the study of whale carcasses brought into the whaling station at Grytviken in South Georgia, were paid for by a tax on whale oil processed in British dependencies. This research was eventually extended all round the ocean to gain the information needed to explain natural variations in the distribution of whales and their

James Clark Ross, perhaps the most accomplished British polar explorer of the nineteenth century. (Bettman Archive)

food. Thirty-six volumes of reports have been published so far, the majority being systematic studies of different species by specialists, though sometimes with notes on distribution. The expedition's scientists themselves usually concentrated on studies of distribution, especially of *Euphausia superba* (krill), the whale food (see Figure 1, page 42). It seems to have taken six or more scientists several years to distinguish and describe all the stages in the krill's life history, from egg to adult, and to learn something about the reproductive mechanism. It took still longer to sort plankton samples from all seasons and areas where the different stages might occur and, in all, 15 to 20 years to reach a reasonable working hypothesis about the overall development and distribution. Other dominant species were studied less intensively, most of them seeming to have a more even circumpolar distribution than the krill, which is strongly influenced by the outflow from the Weddell Sea and by smaller northward currents elsewhere. Quite a lot was learned about the diurnal and seasonal vertical migrations of different

Members of the Ross expedition landing on Possession Island, inhabited by "myriads of penguins." (Bettmann Archive)

U.S.N.S. Eltanin *in loose pack-ice. (NSF)*

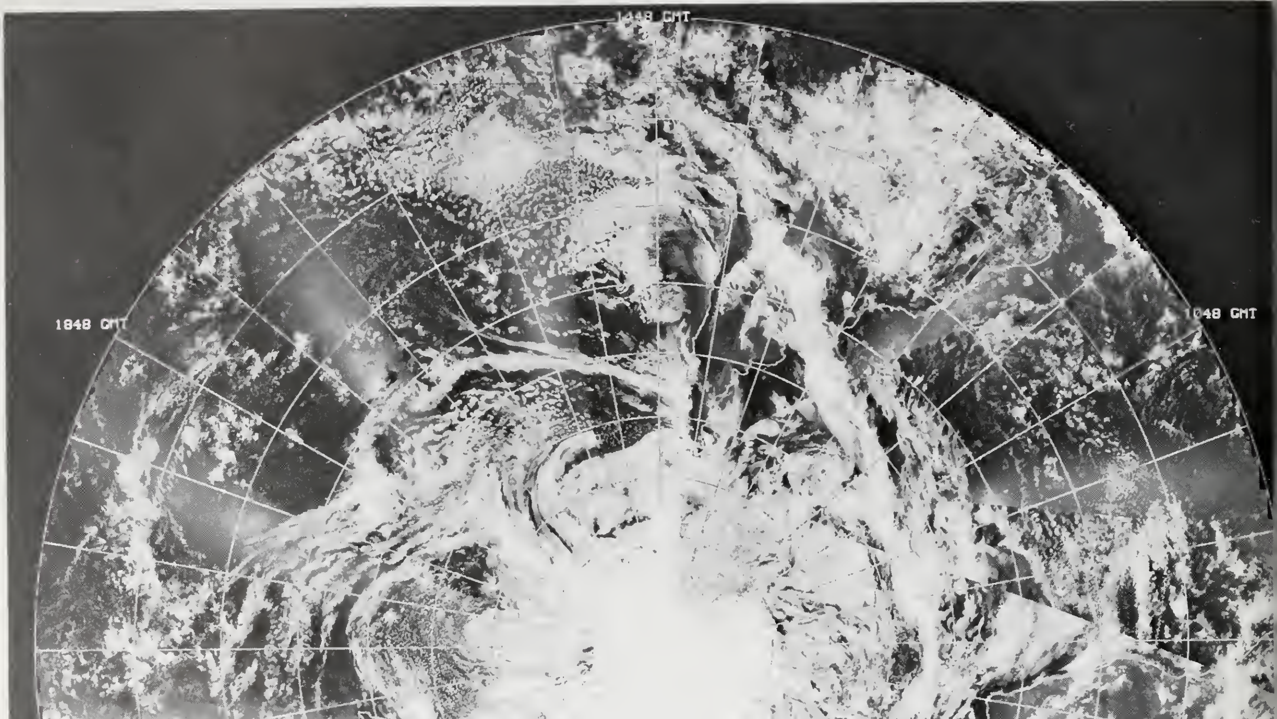
species, which, in association with the water movements, are clearly part of the processes by which the populations and distributions are maintained.

Since World War II, the major contributions to Southern Ocean research have been made by large expeditions from the United States and the Soviet Union, and by the growing interest of Australia, New Zealand, and South Africa. They emphasize the value of new equipment and methods, especially in sea-floor studies, and we now know a lot more about the geological structure, sediments, and benthos. Shore laboratories have made notable advances in studies of the physiology and reproduction of near-coastal species, as well as of their taxonomy. We also have learned a good deal about the water structure and movements as a result of fruitful cooperation between the National Science Foundation and the U.S. Navy and Coast Guard—the work of *Eltanin* being specially remarkable. But it seems that progress in the study of the oceanic plankton, which make the ocean so productive, is still slow. New methods are used extensively for studying general characteristics such as productivity, but we are still left wondering whether the relatively poor standing crop usually found in the northern part of the antarctic zone might not be due to intensive grazing by a rich zooplankton.

Before the Southern Ocean is exploited again, as it was in the past for the seals and whales, we ought to have a sound knowledge of the life histories and an understanding of the distribution of at least some of the dominant plankton species. It will require scientists with a fairly wide range of interests working together on long-term problems and with sufficient continuity to ensure full use of earlier work. There will also have to be a compromise between the continuing use of older methods, which aim at comparability, and the ready adoption of new methods, which introduce some discontinuities into more recent work. Long-term ecological studies are not likely to be very popular with government funding organizations or with scientists who have to promise immediate returns, but perhaps we can hope for long-term commitments by some of the older, established institutions. We begin to need some continuing laboratories or groups specially devoted to the Southern Ocean.

Sir George Deacon, formerly director of the U.K. National Institute of Oceanography, made four voyages to the Antarctic between 1927 and 1937. Still interested in the Southern Ocean, he joined Theodore Foster of Scripps in U.S.C.G.S. Glacier *in 1975.*

Currents, Fronts, and Bottom Water



NOAA-2 photo mosaic of the Southern Hemisphere on January 19, 1973, taken with the visible channel of the radiometer. Photos are assembled from the day's set of orbits; times of the pictures (GMT) are shown around the circumference.

D. James Baker, Jr.

The great polar heat sink in the Antarctic creates a strong interaction among air, ice, and sea. Over the course of the seasons, ice forms and is blown out from the coast. Cold, dense water sinks and helps create the properties of the deep water. Warm water rises to the surface; heat is lost from the ocean to the atmosphere. Strong winds blow the currents round the Antarctic continent. Parts of the deep circumpolar flow peel off from the main current and head northward into each of the major ocean basins.

These processes are all components of the global heat engine that is fueled by the sun and whose moving parts are the atmosphere and the ocean. This engine generates our climate, of which the mean state and variability are of great concern to man's activities. If we are to understand the system and how it responds to changes in various outside forces, we must know the variability as well as the mean.

Remember that the saying "climate is what you expect, weather is what you get" holds true for the ocean as well as the atmosphere. We know something about the mean—the ocean climate—but what is the weather? If we interpret variability correctly, we can find out how the system responds to changes in the forcing. Only after we know how the system responds can we begin to think about prediction for various practical purposes.

There seems to be high variability of the forcing and of the response in the Southern Ocean. Severe storms and cyclones are formed, moved into the region every few days, and then decay. The amount of ice cover on the ocean varies drastically over the seasons and with the wind, and the production of cold, dense bottom water seems to be sporadic.

The Circumpolar Currents

Circumpolar currents play an important role in general ocean circulation. The meridional (north-south) transports of heat, mass, and momentum are closely tied to the zonal (east-west) circulation: changes in one are reflected by changes in the other. There is a distribution of density that supports the meridional flow necessary for linking the antarctic heat sink to the general ocean circulation. This density field requires a zonal current—the circumpolar flows. In turn, changes in the zonal current affect the supporting distribution of density and its associated meridional circulation. Thus, the zonal current responds to the variability of the winds and the ice cover; in turn, there are variations in the heat, mass, and momentum flux into the South Atlantic, Pacific, and Indian oceans (see page 21).

Dynamic topography maps based on data gathered at the many thousands of hydrographic stations in the Southern Ocean show two major features of the circumpolar currents. Nearest the continent, in some areas, is a weak westward flow, sometimes called the "east wind drift" for its apparent cause. The current moves with the wind, but summer ice melting may help speed up or slow down the flow.

Farther from the coast is the mighty Antarctic Circumpolar Current, whose surface waters flow to the east all around the Antarctic continent (Figure 1). Another name for this current is the "west wind drift," after the strong winds at this latitude. The change in velocity with depth of this current (eastward at the surface and decreasing below) is also consistent with the heat flux variation at the surface: cold near the pole and warming toward the equator. Although such heat flux driving can produce a circumpolar flow even in the absence of wind (but only the vertical gradient of velocity is determined), the combination of heat flux and westerly wind is responsible for the net flow, which becomes weaker near the bottom, where it may even be in the opposite direction to the surface. The total transport of the flow is unknown, but it is clear that the total kinetic energy is large enough to make this one of the major current systems of the world.

The Antarctic Circumpolar Current is deflected by at least five major ridge systems as it flows around the Antarctic continent. In some regions it flows across a ridge; in others, parallel to a ridge. There are some areas where the current is divided into several relatively narrow jetlike flows. Near 140°W (Figure 2), one observes loops and waves in the current as it flows, which may indicate that the current is behaving like the Gulf Stream or the Kuroshio (i.e., exhibiting the same kind of time-dependent nonlinear dynamics appropriate for those currents). Figure 3 shows the jetlike nature of the flow parallel to the Indian-

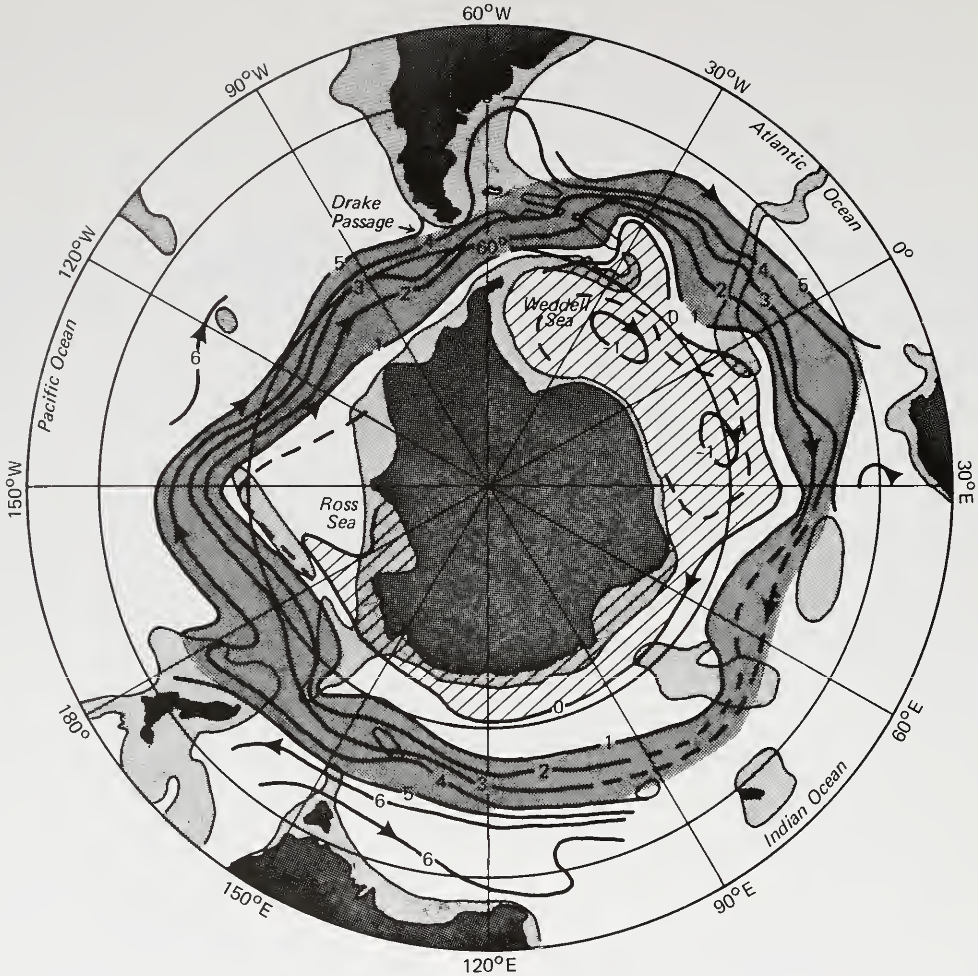


Figure 1. The Antarctic Circumpolar Current as revealed by geostrophic transport lines (between two lines the transport relative to a depth of 3000 meters is 20 million cubic meters per second). Shaded area near the coast includes westward flow and various gyres. Lightly stippled areas indicate depths less than 3000 meters. (Adapted from Deacon, 1937)

Antarctic Ridge. Here the strongest part of the flow is only 200 kilometers wide, and a countercurrent is observed near the crest of the ridge. Once again, this may be reminiscent of western boundary current dynamics, but our theoretical understanding of such a phenomenon is still too obscure.

Recent studies of the variability of the "east wind drift," near the coast, have used the tracks of satellite-monitored icebergs, which twist about and even double back on their original tracks (Figure 4). Loops and turns are common. Theoretical models have not yet incorporated these observations, which suggest that this region is similar to other, more familiar, coastal areas.

Variability of the "west wind drift" is a good puzzle. Although the geostrophic transport relative to a given level has proved to be remarkably constant (to within 10 percent) over the years, recent direct measurements by the Bedford Institute of Oceanography show that the total transport may be very small. And, even though the latter measurements were only for ten days, the current displayed marked changes. The results indicate variability at every level of measurement (Figures 5 and 6). Data from tide gauges on either side of the passage also show changes that could be interpreted as variations in total transport—as much as 50 percent. Are these changes the result of eddies passing through? Does the transport of the current through the Drake Passage change from year to year? If so, where does the water go? These questions and others will be answered only when we get a better theoretical and observational picture of the flows in the Drake Passage.

Further study of the variability of circumpolar currents requires more elaborate and

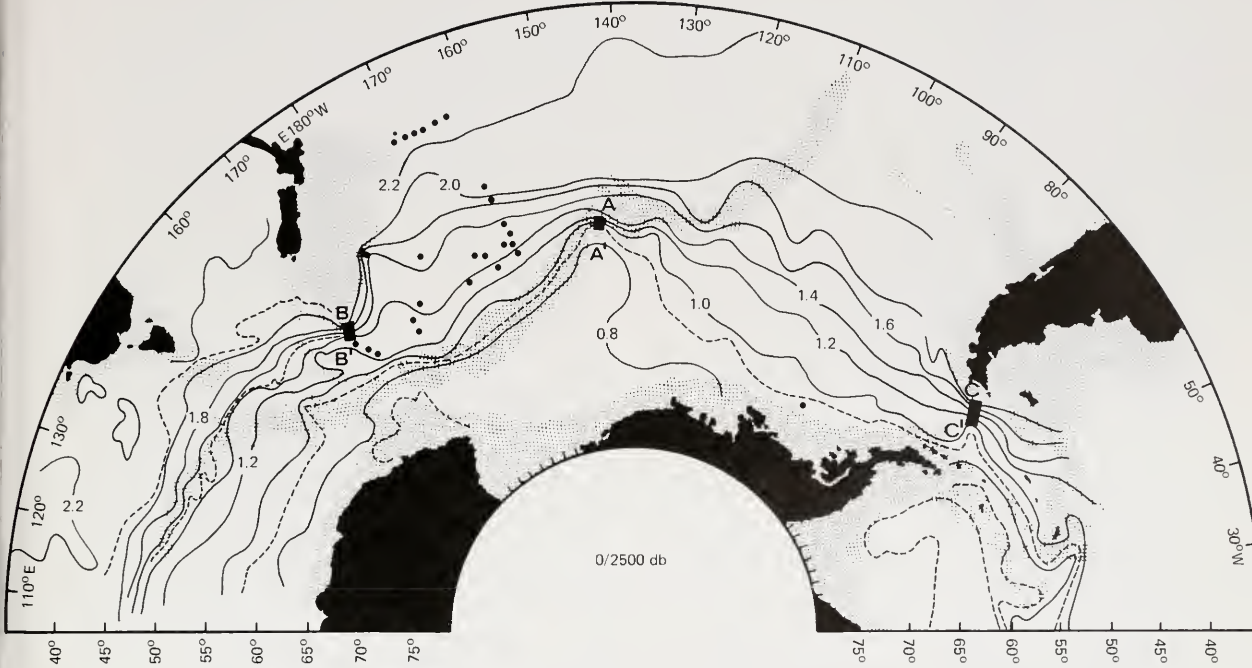


Figure 2. The Antarctic Circumpolar Current in the South Pacific. The sea-surface topography relative to a depth of 2500 meters was constructed from approximately 1000 data points taken over a period of 44 years. Depths less than 3000 meters are stippled. Waves in the current near the constrictions of AA′ and BB′ suggest that the bottom topography affects the flow. (After Gordon and Bye, 1972)

long-term field experiments with modern direct-measuring instruments. Such research is the major goal of the International Southern Ocean Studies (ISOS): a first set of year-long moorings was placed in the Drake Passage in February 1975 by Oregon State University; additional data on the structure of the flow in 1976 and 1977 will be recorded by drifting floats and pressure gauges. It is hoped that a variety of different monitoring instruments can eventually be used to track the flow and its changes.

The Polar Front

There are many areas in the Southern Ocean in which marked changes in water characteristics are observed across short distances. The most commonly known of these "antarctic fronts" is the Antarctic Convergence, so named because early interpretations of the temperature and salinity suggested a sinking of northward-moving Antarctic Surface Water below the less dense southward-moving subantarctic water. More recent and detailed studies, however, have shown that there may be divergent or convergent fields of motion, and detailed sections reveal the existence of many sharp discontinuities in temperature and salinity. Because of the complicated processes in this region, a more appropriate name for it is the "polar frontal zone," which implies neither convergence nor divergence. Figure 7 is a schematic representation of water masses and layers in the Southern Ocean.

The area of the polar front extends all around the continent. Its surface features are often obvious, as described by Dr. D. D. John in a lecture to the Royal Geographic Society in 1934:

It is a physical boundary very easily and precisely detected with a thermometer by the sharp

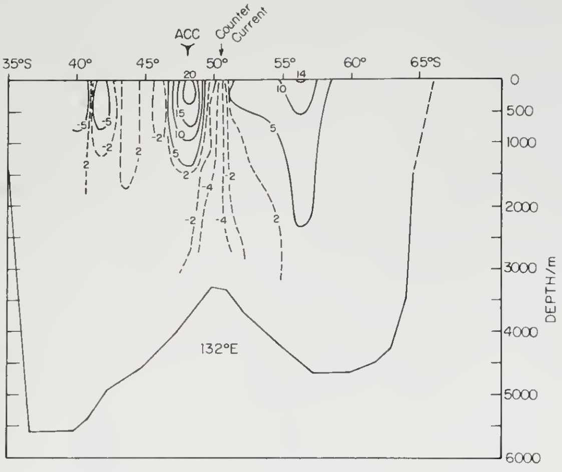


Figure 3. Eastward (positive) and westward (negative) flow in the Antarctic Circumpolar Current (ACC) south of Australia. The narrow core of the ACC and the "counter current" appear to be "trapped" near the crest of the ridge. Vertical exaggeration is 500. (Adapted from Callahan, 1971)

change in temperature as one passes from one zone to another. It can be detected as easily if not so precisely by a zoologist with a tow-net, because each of the two waters has a distinctive fauna of floating animal life. But we, whether sailors or scientists, know and will remember the convergence best in another way: as the line to the north of which we felt one day, at the right season, after months in the Antarctic, genial air again and soft rain like English rain in the spring. I can remember a number of those days vividly. It was like passing at one step from winter into spring. In the Southernmost lands in the sub-Antarctic, the islands about Cape Horn, the earth smells as earth should smell and never as it does in the Antarctic. It is, no doubt, the north-easterly course of the convergence between the longitudes of Cape Horn and South Georgia so that the former is left far to the north and the latter to the south, that accounts for the vast difference in the climate of two islands which are in precisely the same latitude and only 1000 miles apart.

The frontal zone is characterized by interleaving layers, and waters of different temperature and salinity appear to mix in this region. Details of the temperature and salinity structure, if followed as they evolve, could tell something about the mixing processes, the final result of which may be the formation of Antarctic Intermediate Water (Figure 7).

It has been observed that the maximum west wind, the core of the Antarctic Circumpolar Current, and the Antarctic Frontal Zone follow more or less the same path around the Southern Ocean. The explanation of this interdependency awaits the development of a satisfactory model of all these processes.

Variability in the location of and in the processes occurring at the front has been observed. Individual crossings of the zone often show signs of divergence rather than convergence. The sharp surface-temperature change indicates a seasonal oscillation of 100 to 200 kilometers and a long-term change of 400 kilometers from 1901 to 1960. Large cyclones appear to track along the frontal zone and to affect zonal processes during their passage.

The first step in studying this complex region is to measure directly the currents in the zone. Plans are now in progress in ISOS to use drifting floats that record both horizontal and vertical velocity. The floats will be used to "see" the effect of passage of storms on the ocean, and to verify whether sinking or rising motion is characteristic of the region. Theoretical work has begun to study the relation of the Antarctic Circumpolar Current to the frontal zone: for example, whether the Circumpolar Current interacts with bottom topography and produces frontogenesis independent of the winds, and how the fronts respond to changes in the winds.

We hope that the initial direct measurement will point the way toward eventual serial measurements with very high vertical resolution of the evolving temperature and salinity fields. Then we will be able to learn about the vertical mixing processes in the area and to determine how the various water masses are formed.

Bottom Water Formation and Outflow

High-salinity water is cooled near the Antarctic continent and sinks near the coast to become Antarctic Bottom Water. The distribution of properties in the ocean shows that the deep flow moves northward along the western boundaries of each of the Pacific, Atlantic, and Indian oceans. Over half of the water in the world ocean is affected by this cold, dense bottom water. The highest concentration of the coldest water is found in the Weddell Sea (-1.4°C)—hence the theory that this region is the major source. But water dense enough to be bottom water has also been found in the Ross Sea and along the Adélie Coast.

Bottom water apparently plays an important role in the antarctic heat balance. The northward transport of cold bottom water,

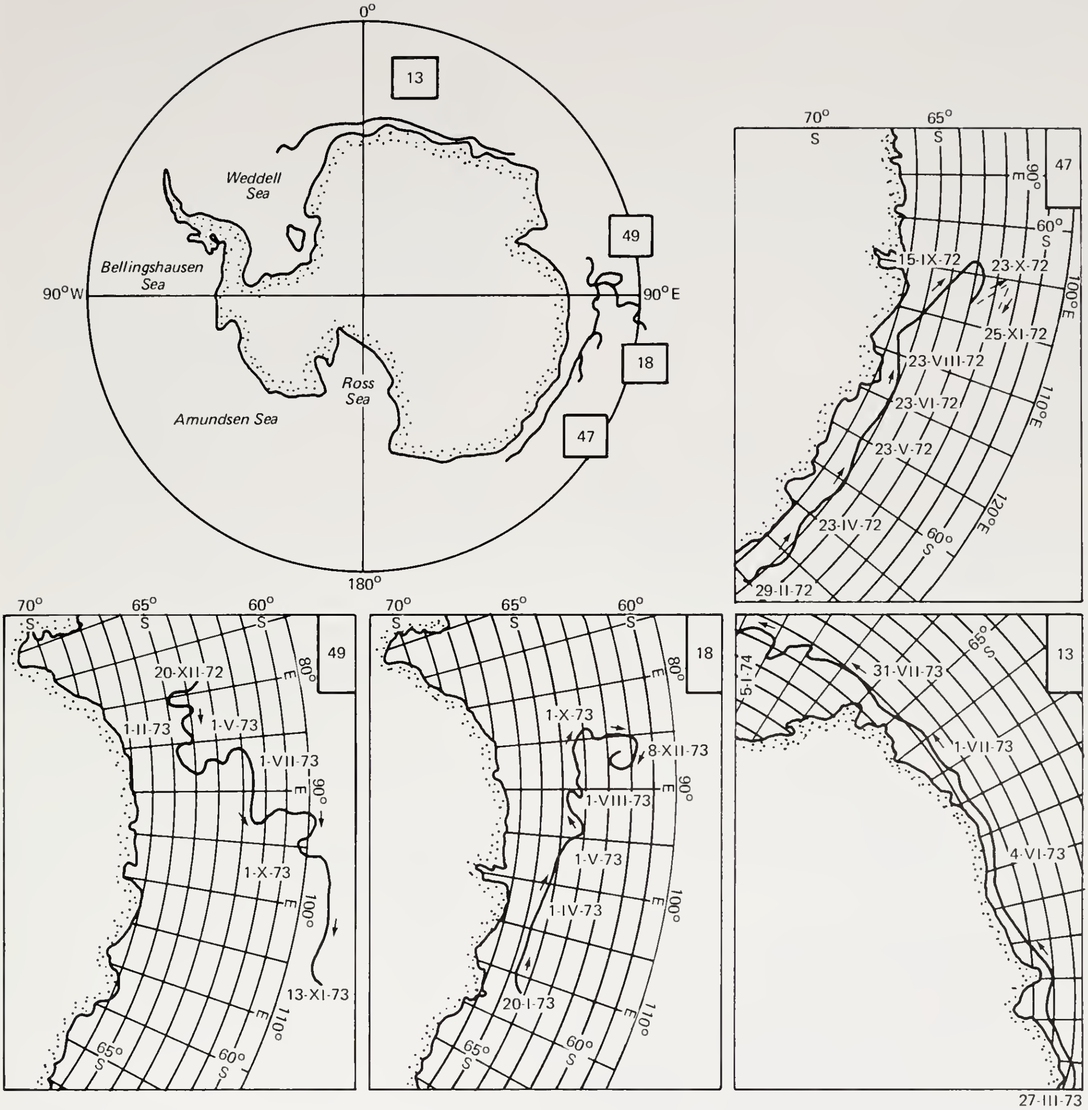


Figure 4. Icebergs drift westward near the continent, showing the effect of both westward surface current and westward winds. (After Tchernia, 1974)

accompanied by a southward transport of warmer, returning, deep water, balances the heat loss in the winter. Also, the strong meridional circulation causes great mixing of chemical constituents and upwells nutrients for the fish (see page 37).

Both the formation rate and the outflow rate of bottom water are believed to be highly variable. Although the actual mechanism for bottom water formation is not known, the most likely seems to be the following: Cold winds whip down from the continent and freeze ice at the surface, causing an increase in the salinity and a decrease in the temperature of the water; this cold high-salinity (and therefore more dense) water sinks and mixes with the deeper, warmer, and saltier water at the edge of the shelf; and the combination then sinks to the bottom. Although there have been no direct measurements of this process in the Antarctic, measurement in the Mediterranean of the sinking of cold surface water showed it to be highly localized and intermittent. The areas of formation of Antarctic Bottom Water will probably prove to be as elusive to find.

Our knowledge of outflow variability is likewise scanty. The few measurements we do have serve to prove the existence of the outflow, but not how it changes. L. Valentine Worthington of the Woods Hole Oceanographic Institution argues that

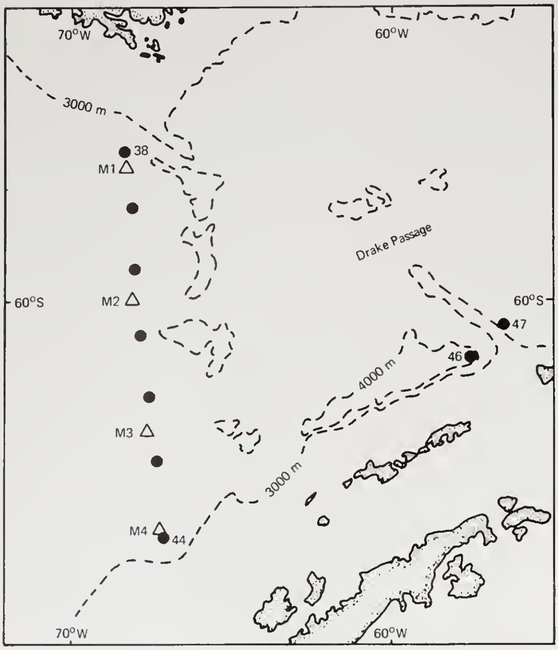


Figure 5. Location of Bedford Institute current meters, M1-M4, 1970. Dots represent hydrographic stations. (After C. R. Mann, unpublished report)

the distribution of properties in the ocean suggests a surprising result: negligible production of Antarctic Bottom Water in the twentieth century. The argument is the following: Antarctic Bottom Water, rich in dissolved silicon, flows northward into the ocean basins. It must return southward in the upper layers to conserve mass. However, the upper layers are poor in dissolved silicon. A net northward flow of as little as 15 x 10^6 cubic meters per second of Antarctic Bottom Water across 28°S in the Pacific Ocean would require a removal of 20 x 10^{14} grams of silica per year. No reasonable mechanism for this removal has been deduced. Thus, Worthington believes that the distribution of dissolved silicon in the ocean is more consistent with negligible production of Antarctic Bottom Water, at least in the twentieth century, for which the measurements are representative. However, observations of bomb-produced tritium in the deep waters of the South Pacific by the Scripps Institution of Oceanography show radioactivity well above the natural level, suggesting that some deep water could have come from the surface in the last ten to twenty years.

To verify theories on variability, such as Worthington's, long-term observations and arrays

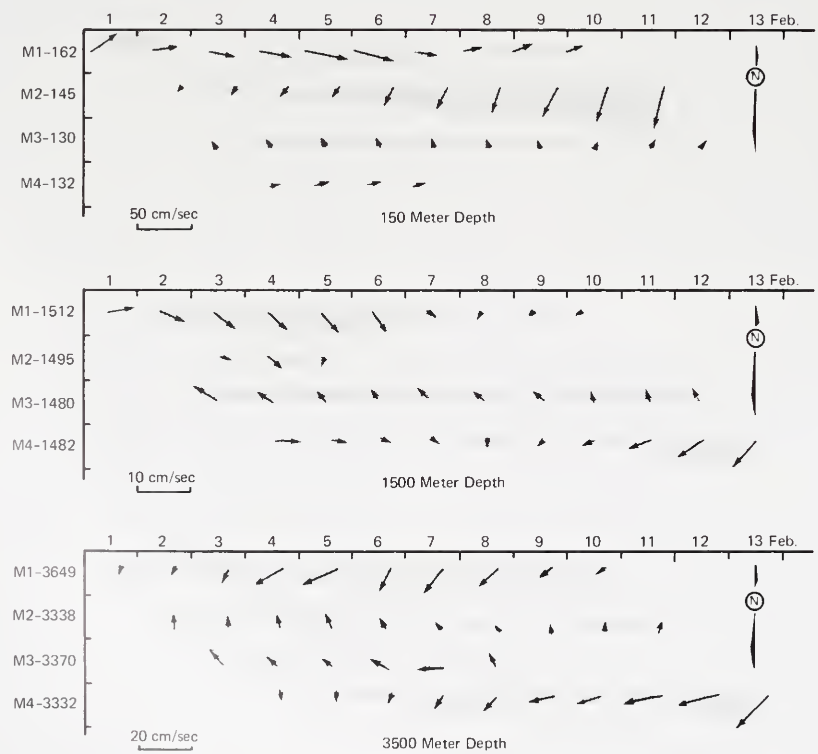


Figure 6. Velocity vectors from Bedford Institute current meters, 1970. The large variability in magnitude and direction shows that much longer records from closely spaced instruments will be required to adequately document the flow. (After C. R. Mann, unpublished report)

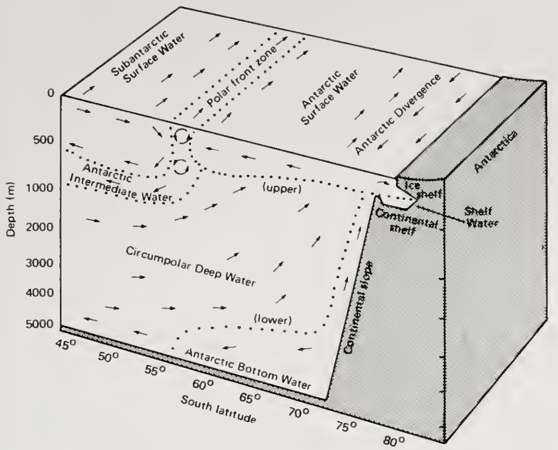


Figure 7. Schematic representation of water masses and core layers in the Antarctic and Subantarctic. The southward flow of Circumpolar Deep Water is compensated by the northward flow of Antarctic Surface Water, the associated Antarctic Intermediate Water, and the Antarctic Bottom Water. (After Gordon and Goldberg, 1970)

of instrumentation are required. There is still no good technique for monitoring hydrography under an ice sheet; repeated passes with a submarine may be required. In the meantime, the use of current meter moorings in likely places is the best method. But even this is not easy. In 1968 scientists from the Bergen Institute of Geophysics put out several current meters for which they planned to return the following year. The ice was too thick then, however, and the meters could not be recovered until 1973, by which time the batteries had long since run down. Nevertheless, the scientists obtained the longest current meter record to date—more than a year. Marked changes in the flow are seen, but the interpretation is still ambiguous.

A series of international Weddell Sea oceanographic expeditions are completing a survey of the summer hydrography of the region. This work, together with feasibility studies of the collection of winter hydrographic data, will lay the groundwork for more extensive observations in the future.

Conclusion

All of these studies of Southern Ocean dynamics can contribute significantly to an understanding of several areas of global concern. From a biological standpoint, monitoring of the physical oceanographic environment is a necessary adjunct if man is to harvest efficiently, but not exhaust, the resources of this richly productive area (see page 45).

The disposal of waste and radioactive by-products is of major environmental consequence. Overturning rates and processes in the Southern Ocean must be understood and monitored before we can predict the residence times for these man-made pollutants. An ecologically sound strategy awaits our understanding of the deep circulation of the ocean.

Through the experiments mentioned above, and other air-sea interaction and meteorological research now underway or being planned, oceanographers and meteorologists hope to define the role of the polar regions in oceanic and atmospheric climate.

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Atmosphere and Ice

Uwe Radok, Neil Streten, and Gunter E. Weller

For the meteorologist the Southern Ocean begins at the southern border of large persistent high-pressure regions found around 30°S over the Atlantic, Indian, and Pacific oceans; and at the southern coasts of South Africa and Australia, with their winter rains and their extreme temperature changes as the air flow comes, in turn, from the heated land to the north or from the perennially cool sea to the south. These changes come in response to a continual succession of high-pressure ridges and low-pressure wedges noted by the first observers as a peculiarity of the southern atmosphere (Figure 1).

These weather systems are anchored farther south in the migrating depressions and anticyclones that create the "brave westerlies" of sailing ship fame in latitudes between 40° and 60°S. On their polar side these large eddies give rise to a third zone, that of the polar easterlies and of the pack-ice that spreads each winter from the antarctic coast to enlarge the total ice-covered area by a factor from 2 to 3. Still farther south the Southern Ocean ends in the coastal ice cliffs and ice shelves of Antarctica, often separated from the pack-ice by belts of open water, "polynyas," created by currents and by the violent winds flowing off the antarctic ice sheet.

The different zones are only too conspicuous as one travels south toward the continent. The initial subtropical blue skies and shallow stratocumulus clouds become more dramatic as the sea puts on the huge breakers and swell of the westerlies and the clouds grow into white-and-black cumulonimbus formations, with rain and snow showers in between clear breaks of dazzling brilliance. But soon the colors fade and everything turns gray, the only contrast provided by the unnatural white of stray icebergs wallowing menacingly in the heavy seas. At times the gloom persists right into the pack and up to the antarctic coast, but as often the ship will break through into a new dazzling white-and-blue seascape of calm water, icebergs, and marine life, as the antarctic ice sheet emerges like a line of low clouds stretching from horizon to horizon.

Edge of the Ross Ice Shelf. (A. W. Erickson)

Atmosphere

An account of the atmosphere over the Southern Ocean conveniently starts at the highest levels and proceeds downward to the ocean surface. This is not because the high-level phenomena are simpler, but because the lack of detailed information makes their complexity less obvious. The problems in the stratosphere and upper troposphere concern, on the one hand, the broad eastward air flow (the upper westerlies, in meteorological parlance) and, on the other, the associated meridional circulations that help to balance the momentum and energy budgets of the southern hemispheric, indeed the global, atmospheric circulation, and in so doing transport various natural and man-made substances to their ultimate deposition on the Southern Ocean and the antarctic ice sheet.

An especially important substance in this context is ozone, which is constantly formed and dissociated by ultraviolet radiation and molecular collisions at levels around 40 kilometers, but which becomes a persistent "tracer" substance in the air currents at lower levels before ultimately being destroyed by reactions with the surface. Somewhat higher stratospheric temperatures around 60°S suggest the existence in these latitudes of a descending current that produces both over the South Pole and over middle latitudes increased concentrations of ozone, and presumably also of other chemicals and small particles suspended in the stratosphere. In the course of the year, this stratospheric circulation pattern undergoes significant changes, some of which are connected

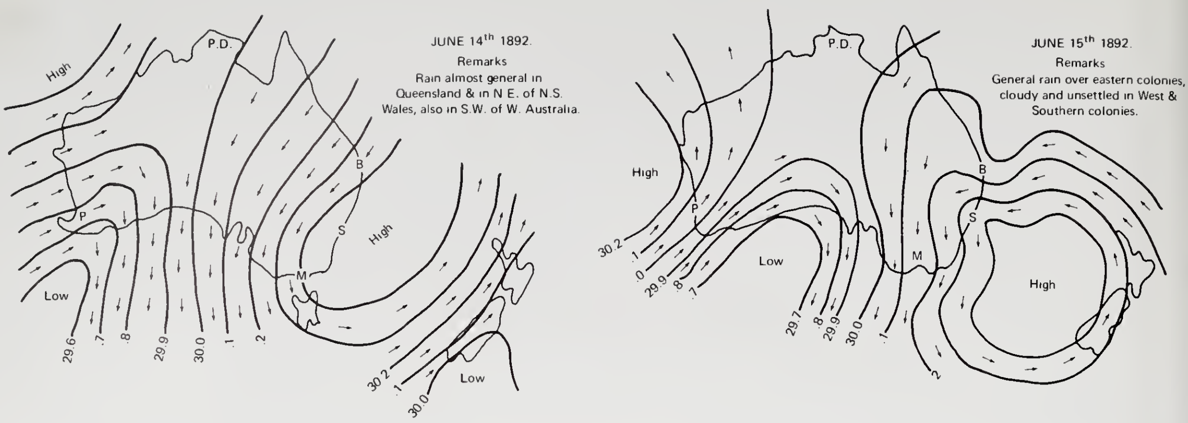


Figure 1. Moving anticyclones in the Southern Hemisphere. (After Russell, 1893)

with sudden marked temperature increases around the time of the spring equinox; the underlying processes remain obscure, but the accumulating observations from satellites promise steadily increasing understanding of the stratospheric events and their effects on the upper troposphere.

The circulation of the upper troposphere is somewhat better documented by direct observations with ballons, and moreover is made visible in parts by clouds in satellite photos. A schematic view of the circulation patterns thus established is shown in Figure 2.

The main features of the Southern Ocean atmosphere clearly appear in this combination of plan view and vertical cross-section. In the plan view the westward trades in low latitudes emerge from the descending and diverging air in the quasi-permanent anticyclones around 30° S, which ultimately returns via the tropics and the vertical "Hadley" circulation. Poleward of the high-pressure belt, the flow breaks down into large eddies and a melee of cold and warm air masses separated by "fronts." In the vertical section their statistical composite is the "polar front" (PF), which corresponds to a net ascent of air in middle latitudes, compensating the downward flow produced by intense cooling in the polar atmosphere during most of the year.

Jet Streams

In close similarity to the ocean, the atmosphere tends to concentrate the higher-level flow into narrow high-velocity currents, the "jet streams." The principal of these are the subtropical jet stream J_S, marking the concentration of the main temperature contrast between equator and pole into a narrow zone above the subtropical anticyclones; and the polar-front jet stream J_P, associated with the more regional temperature contrasts between the different air masses over the Southern Ocean. The existence and structure of the jet streams were deduced originally around 1950 from temperature observations, in the same way ocean currents are derived from density fields. Direct wind measurements from radar-tracked balloons subsequently confirmed the existence of very strong winds over the few areas of the Southern Hemisphere where such measurements are feasible. More recently, satellite techniques have provided a number of new possibilities for studying the jet streams in detail.

One technique utilizes balloons made of non-expanding plastic and filled with a precisely calculated quantity of hydrogen or helium that lifts them to the level of the strong winds and keeps them floating at that level. The progress of the balloons is then reported by tiny transmitters to a communications satellite. Some of the balloons launched in U.S. and French programs from New Zealand have circled the Southern Hemisphere more than 35 times, and the analysis of the accumulated tracks has provided a more detailed picture of the intricate changes in the strong currents above the Southern Ocean. A large experiment of this type is planned for the first global experiment in the Global Atmospheric Research Program (GARP), known as FGGE and tentatively timed for 1979. By then the balloons will report not only their positions but also the air temperature—crucial information for understanding the jet stream mechanisms.

Temperature changes associated with the jet streams already form the basis of another method for their detection by means of satellites. As indicated in Figure 2, the jet streams are associated with circulation patterns that carry dry stratospheric

air downward into the troposphere on the poleward side of the jets. This displaces the tropospheric water vapor into the lower and warmer layers of the atmosphere and increases the intensity of the radiation emitted by the water vapor absorption bands, notably that near 6.3 microns. As a result, a dark band following the course of the jet stream appears in satellite photos taken with terrestrial radiation at that wavelength, making the jet visible.

By these means the complicated morphology of the intense wind bands over the Southern Ocean, originally hidden by the lack of island stations, is starting to emerge. There appear to be no fewer than four separate jet streams, each characterized by its own distinctive combination of altitude and temperature; moreover, jets are more prevalent over some sectors of the Southern Ocean than others—a fact already surmised from the analysis of conventional observations, embodied in an atlas of Southern Hemisphere climatology published by the National Center for Atmospheric Research (NCAR).

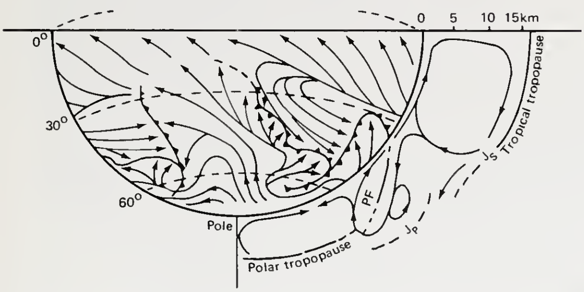


Figure 2. Schematic model of the general circulation in meridional section, and schematic fronts and streamlines at the earth's surface. (After Defant and Defant, 1958)

Some jet streams also show up through their characteristic clouds in infrared cloud photos taken by various meteorological satellites, but these photos mainly relate to the depressions of the middle and lower troposphere. In fact, an examination of satellite mosaics of total cloudiness averaged over weeks or months indicates strikingly persistent cloud bands over particular regions, notably the central South Pacific and South Atlantic. These bands tend to lie near the lower-latitude arms of the climatic polar fronts, and agree with the locations of fronts that have been inferred from subjectively analyzed weather charts, and from the regional frequency of strong 1000-to-500-millibar-thickness gradients. Figure 3 shows the mean summer axes of the polar front superimposed on a 16-day cloud cover image in December.

Depressions

Within these frontal zones most frequently develop the depressions that are the chief features of the weather of the Southern Ocean. In satellite mosaics these systems may be identified by their characteristic cloud vortices. Figure 4 shows a computer-generated mosaic of the Southern Hemisphere as viewed in infrared over a 24-hour period from the polar-orbiting NOAA-1 satellite. In this typical view the great cloud vortices are seen in their continually varying stages of growth and decay, as they move eastward and poleward at some 800 to 1200 kilometers per day over the Southern Ocean.

Such systems are often described as gigantic turbulent eddies embedded within the stream of the westerlies, but they differ from ordinary wind and water eddies in having complex internal structures and energy sources (radiation and condensation pressure). They serve as the primary link with the southern part of the atmospheric heat engine by achieving poleward and equatorward transfers of heat, moisture, and momentum across the middle latitudes of the hemisphere.

The life history, tracks, and intensities of the depressions have attracted interest from the earliest years of synoptic analysis over the Southern Ocean, when clues to their behavior were pieced together (often retrospectively) from fragments of information from isolated island and antarctic expeditions. Now, however, by comparison of the cloud vortices viewed in sequences of hemispheric mosaics with conventional observations, the

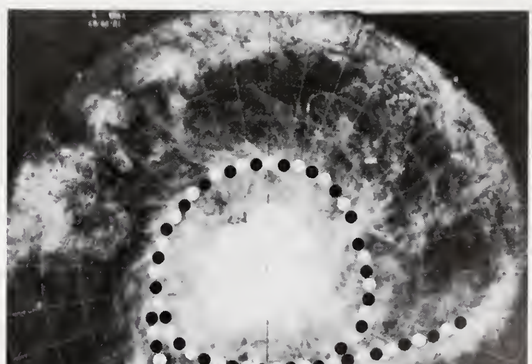


Figure 3. Cloud cover of the Southern Hemisphere photographically averaged for the period December 16–31, 1967, by J. Kornfield and A. F. Hasler, University of Wisconsin. Dotted overlay shows the mean location of the polar front in summer. (After Taljaard, 1968)

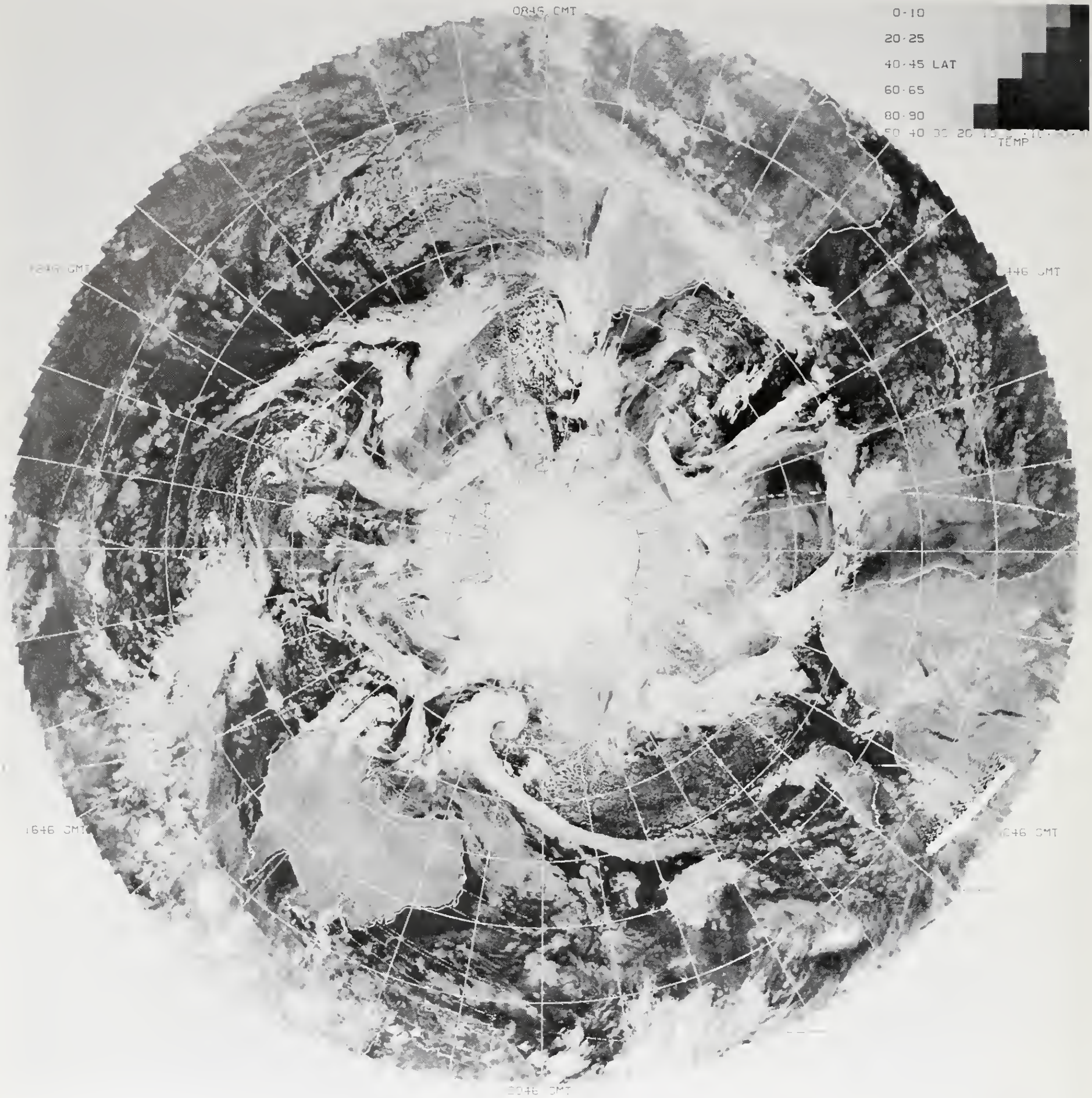


Figure 4. NOAA-1 infrared photo mosaic of the Southern Hemisphere, June 18, 1971. Note that the continents are depicted lighter (colder) than the warmer ocean on this winter night, and that the brightest (highest and coldest) clouds appear in the Southern Ocean depression vortices and in the tropical systems over Indonesia. A gray scale shows approximate temperature values in ^{o}C. Photos are assembled by digital processing of the images from a day's set of orbits; the times of the pictures (GMT) are shown around the circumference.

meteorologist is able to build up a more reliable analysis.

The first step has been to identify a number of cloud vortex types, each with a distinctive "signature," or cloud pattern. Many hundreds of comparisons between satellite pictures and synoptic weather charts have made it possible not only to interpret each form of cloud spiral as a definite stage in the evolution of the cyclonic eddy, but even to estimate the corresponding approximate intensity of the system, i.e., its central pressure at that stage.

Furthermore, the growing satellite material is beginning to show in increasing detail how these eddies are moving at different times of the year and in different years. Figure 5 shows tne predominant tracks constructed in this manner, but it is important to emphasize that marked deviations from this typical behavior can occur in individual seasons or years. A striking example derived from the conventional observations of the IGY is given in Figure 6, which compares the cyclone tracks in the region of the Drake Passage during periods preceding

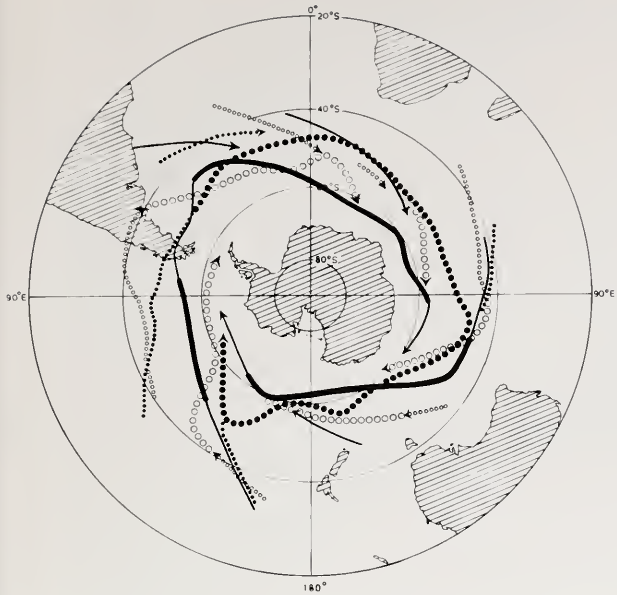


Figure 5. Vortex track diagram. Heavy lines are major tracks, finer lines minor tracks. November (open dotted); January (full dotted); March (full line). (After Streten and Troup, 1973)

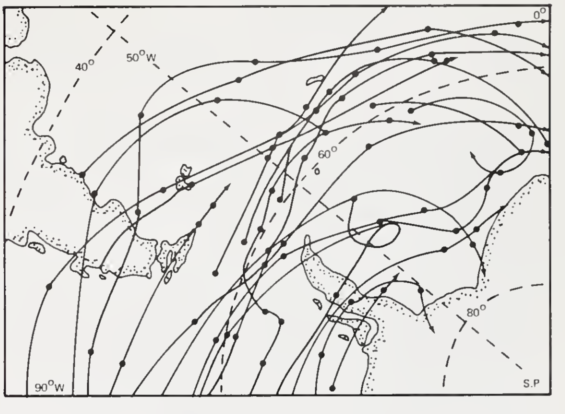
and following one of the periodic El Niño* displacements of the Humboldt Current. The different behavior of the weather systems on the two occasions makes it conceivable that the El Niño phenomenon originates from, or at least is prepared by, interactions between the Southern Ocean and its atmosphere; and its latest occurrence among the climatic disasters of 1972 and 1973 points to the possible global significance of these interactions.

Energy Transfers

The more direct and obvious effect of the winds of the southern weather systems is to produce the ocean currents, discontinuities, upwellings, etc., discussed elsewhere in this issue. The meteorological discussion will be concentrated on another aspect of the atmosphere-ocean interaction: the various transfers of energy that take place not only in the depressions but especially in the intervening calmer high-pressure regions, marked in the satellite photos by scattered clouds or simply the absence of clouds. Information on the energy quantities involved is now also beginning to come directly from satellites, but the existing picture must be pieced together from various oceanographic cruises, notably the momentous 10-year survey made by U.S.N.S. *Eltanin.*

Typical magnitudes of meteorological parameters associated with the weather systems of the Southern Ocean are shown in Figure 7, which sums up the average experience of passing through a frontal zone between contrasting air masses. The air ahead of the front, coming from lower latitude, is a little warmer than the water and consequently transfers some of its heat to the ocean surface as "sensible heat flux." At the same time, the air is being enriched with water vapor, and this means a loss of "latent heat" for the ocean, since the vapor will subsequently condense in a cloud and release to the atmosphere the heat of evaporation originally supplied by the ocean.

On the western side of the front, both these fluxes are much larger and directed from the ocean to the air, since the air now comes from the polar side and is colder than the ocean water. The magnitudes shown are characteristic of the region of the greatest sea surface temperature gradient around 50° S, which also has the largest number of



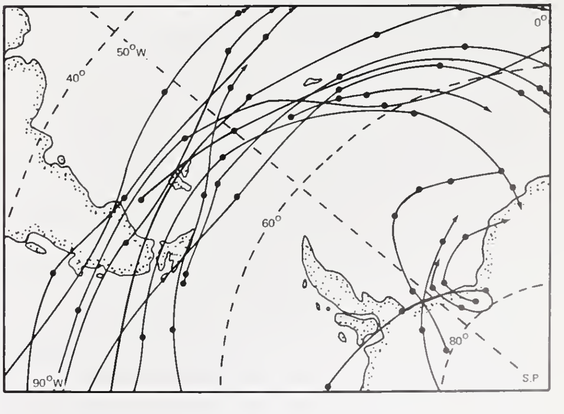


Figure 6. Daily positions and tracks of cyclones in the South American sector during July 1957 (top) and July 1958 (bottom). (After Taljaard, 1967)

*El Niño: Spanish, the Christ child. Phenomenon near the west coast of South America, which occurs sometimes near Christmas, when the trades weaken or are displaced, and upwelling of cold nutrient-rich waters ceases, with disastrous consequences to the anchoveta fishery.

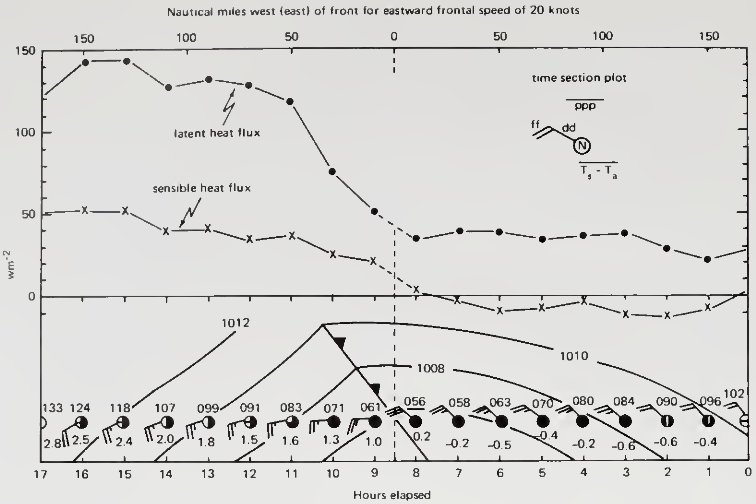


Figure 7. Pressure, wind, cloud cover, sea-air temperature differences, and sensible and latent heat fluxes averaged at hourly intervals before and after the passage of five fronts between 40^o and 50^{o}S. (After Zillman, 1972)

fronts and developing storms. Farther south, over the year as a whole, less energy is received in the form of radiation and exchanged between the ocean and the atmosphere; but within each year, the total energy flux changes from a substantial heating of the ocean in summer (equal to approximately one-tenth of the "solar constant," or radiation intensity outside the atmosphere) to a similar cooling in mid-winter. Both vary little with latitude, although the different fluxes making up the total do; in particular, the sensible heat flux in winter increases markedly, to almost 50 percent of the total exchange, while at the same time the latent heat flux drops by about 40 percent, as one moves south toward the edge of the pack-ice.

Equally marked differences exist between different parts of individual synoptic systems and play a crucial role in the behavior of these systems. At the same time, the weather systems, by stirring the ocean, tap its heat reserves and significantly change their accessibility. Even though the total heat stored in the surface mixed layer is immense in comparison to the heat capacity of the atmosphere, the atmosphere itself largely controls the energy quantities it extracts at any time. Details of this process have so far been subjected to only sporadic observation, but the development of floating buoys and other means of ocean monitoring offers hope of a drastic improvement in the near future, at any rate as far as the open waters of the Southern Ocean are concerned.

Ice

Much greater difficulties arise, however, when open waters become covered by ice. This dramatic process, which effectively doubles or triples the size of the continent each year, commences in the coastal regions of the Antarctic continent. The steep coastal slopes of the continental ice sheet are swept continually by strong katabatic winds, created when radiational cooling of the ice surface sets up steep temperature gradients near the surface and the cold air layer in contact with the ground begins to slide downslope under the action of gravity. Drift snow is inevitably carried in large quantities by these winds, until all the loose accumulations of snow on the hinterland, for hundreds of kilometers back, have been swept out to sea. Day after day, deluges of drift stream over the coastal ice cliffs into the sea; at times the drift is so dense as to obscure objects only a meter or so away. Douglas Mawson, an Australian scientist who headed an expedition from 1911 to 1913, described his experience of the almost constant blizzard conditions in Adélie Land, which he called "home of the blizzard":

> A plunge into the writhing storm-whirl stamps upon the senses an indelible and awful impression seldom equalled in the whole gamut of natural experience. The world a void, grisly, fierce and appalling. We stumble and struggle through the Stygian gloom; the merciless blast—an incumbus of vengeance—

stabs, buffets and freezes; the stinging drift blinds and chokes.

In the mass balance of the Antarctic continent, drift snow carried out to sea by the coastal katabatic winds and storms may amount to about 10 percent of the mass loss, but more importantly, it cools the near-coastal waters and provides them with countless freezing nuclei. When air temperatures fall sufficiently, a thin ice sheet forms eventually, is broken up by wind and waves and carried away from the coast, forming new freezing nuclei.

Ocean water of salinity 33 $^{o}/oo$ starts freezing at a temperature of $-1.8^{o}C$. The most common initial form is "pancake" ice, a collection of irregular round floes measuring about half a meter across (Figure 8) and shaped by the constant collision of neighboring pieces of ice, tossed about by the waves during the freezing process. The subsequent thickening of the ice involves complex processes in the water as the salt is rejected by the ice crystals and partly removed by convective downward currents of heavier saline water, while the remainder of the salt is trapped as brine by the crystals. At the same time, ice freezing can occur in the water column below the ice; the ice crystals thus formed float upward and attach themselves to the "congelation ice" formed at the surface as "underwater ice." A further ice form is produced when heavy snow loads depress the actual sea ice and become soaked with water, turning into "infiltration ice."

From these processes arises the annual ice cover of the Southern Ocean (Figure 9), which forms each year around March or April and grows outward from the antarctic coast to reach its maximum extent in September or October. Centuries of sporadic ship observations had established the average positions of the ice edge in different months, which can be found in various oceanographic and climatological atlases. But satellite imagery, especially in the microwave part of the spectrum that is not impeded by clouds, is now revealing for the first time the detailed features of the ice growth and decay in the course of a year and the changes in the pack-ice distribution from year to year. Figure 10 shows the growth of the ice during 1974.

Influences of Sea Ice

Large variations in the extent of ice between different years have been recorded and raise the possibility that the sea ice plays important roles in the climate of the Southern Hemisphere or even the

Figure 8. Mixed pancake ice and small cake ice. (A. W. Erickson)

Figure 9. Sea ice: small floes. (A. W. Erickson)

globe. For although the southern sea ice at its largest extent (2×10^{16}kg) accounts for no more than 0.08 percent of the mass of the world's ice, it covers almost 6 percent of the total ocean area and almost 30 percent of the Southern Ocean south of 40°S latitude; and its melting requires the energy equivalent of 16,000 100-megaton bombs. One immediate consequence is that the melting of the Southern Ocean sea ice delays the springtime rise in temperatures well beyond the rapid increase in radiation around the spring equinox and creates a steep temperature gradient, associated with strong winds between the pack-ice zone and the rest of the hemisphere in September and October.

More subtle effects of Southen Ocean ice on the overlying atmosphere can be deduced again by comparing the various forms of energy transfers in the presence and absence of an ice cover. It has been estimated that the energy gain of the surface by radiation is halved, and the net energy loss of the atmosphere increased by 50 percent, when the ocean becomes covered by ice. These figures, derived from pre-satellite climatological information for the Southern Hemisphere and the more detailed results for arctic sea ice, have served for a first guess at the consequences of fluctuation in the antarctic sea ice extent for the global climate. The conclusion reached was that an increase in southern sea ice should create more temperate conditions, especially in the Northern Hemisphere, due to the increased circulation intensity and poleward heat flow from the tropics produced by the greater temperature contrasts between the tropics and higher latitudes of the Southern Hemisphere.

This reasoning may not meet the full facts of the complex system, however, since the atmosphere over the Southern Ocean has many "degrees of freedom" for its reaction to, and indeed interaction with, the sea ice. Figure 11 is a schematic representation of the main processes that must be taken into consideration. The most crucial one can only be inferred from the diagram, however. This is the closing or opening of the pack by wind stresses and ocean currents. Arctic measurements show that the heat transfer from the ocean to the atmosphere in winter is greater by two orders of magnitude over sea ice "leads" (openings in the ice) than over the unbroken pack.

At present the consequences for atmospheric disturbances are not yet fully understood and form a key problem now under investigation in both polar regions.

While in the arctic the perennial ice of the polar basin provides a platform for protracted measurements, the impermanence of most of the antarctic sea ice makes it necessary to rely to a large extent on remote sensing, supported by ground truth studies from icebreakers. Luckily, the various satellite systems now in operation provide a wealth of relevant information. By selecting and

making composites of the darkest regions in photos taken with visible light, the boundary between the water and the bright ice is revealed in summer; the same can be achieved for winter with infrared photos in which the relatively warm water stands out by its more intense thermal radiation. High-resolution images in both the visible and the infrared show such details as leads and regions of predominant pressure ridging. Other ice features are revealed by surface emission in the microwave part of the spectrum (around wavelengths of 10–20 mm) that is not impeded by clouds and represents the combined effects of the ice temperatures and the physiochemical state of the ice, so that thin new ice carries a different "signature" from thicker perennial ice. Dry or wet snow on the ice produces further drastic changes in radiance, but a great deal of ground truth remains to be obtained before these details can be firmly interpreted and linked to atmospheric processes. This in itself is merely a preliminary step to inserting those processes in models of atmosphere and ocean that can provide firmer indications of the consequences in terms of weather, ocean currents, cold bottom water formation, etc.

One further step along the same road is to deduce the climatic effects produced by sea ice. All along the antarctic coast, temperatures tend to change systematically from year to year, with large segments experiencing warmer than usual conditions and the remainder, colder conditions. Preliminary examination has shown the sea ice to be more extensive in the colder sectors, and has provided quantitative relationships between temperature anomalies at the coast of the Southern Ocean, on the one hand, and the duration and latitudinal extent of the sea ice, on the other; thus, a lowering of the annual mean temperature by one degree seems to add about 70 days to the duration of the sea ice cover and to push the edge of the ice some 250 kilometers farther north. But the question of cause and effect remains unanswered; again, its solution will involve all the complex interaction processes between the Southern Ocean and its atmosphere.

Glacial Ice

The processes outlined above may be regarded as a form of interaction of the antarctic ice sheet with the Southern Ocean through the intermediary of the southern atmosphere. But the ice sheet also makes a direct input to the Southern Ocean through large masses of "glacial" ice (formed by the sedimentation of countless years of snow precipitation), which each year calve off the ice sheet and enter the ocean. Especially the gigantic tabular icebergs produced along the ice "barriers" of the Ross, Weddell, and Amery ice shelves, as well as by numerous smaller shelves and ice tongues, are unique features of the Southern Ocean and present a host of fascinating problems.

The total mass of icebergs found at any one time in the Southern Ocean has been estimated from ship observations as about one-third of the mass of the antarctic pack-ice at the time of its greatest extent. The annual iceberg production appears to be about one-quarter as large, giving the average antarctic iceberg a life of around four years. But the largest bergs last very much longer and, in fact, by running aground can gradually turn into ice domes and nuclei of new ice sheets.

Iceberg drift can now be observed in detail by means of automatic devices that are planted on the bergs by helicopter and subsequently report their position to communication satellites. But there is an extended historical record of iceberg sightings going back to the first observations made by Cook in 1773. Figure 12 shows the reports collected since then until about 1960 and underlines the low latitudes reached by isolated icebergs. The circumstances are not known, but it appears from the records that the Southern Ocean at different times carried significantly more glacial ice than at present. One such period occurred in the 1830s, and it has been claimed that by forcing sailing ships into lower and calmer latitudes, the ice contributed

Figure 10. Satellite-derived ice extent in the Southern Ocean, 1974.

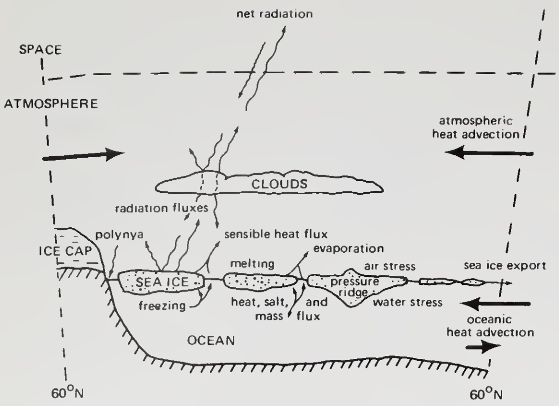


Figure 11. Schematic representation of component processes of the heat budget in the pack-ice zone of the Southern Ocean. (After Untersteiner, 1974)

to their decline and the rise of steam navigation.

Such anomalies in the incidence of icebergs have fundamental implications, since they hint at a potential capacity of the antarctic ice sheet to shed some of its mass at an accelerated rate. For the Southern Ocean and its atmosphere, even a relatively small "surge" would bring a series of interlinked consequences, essentially similar to those of a greatly expanded mass of sea ice, which have been estimated to lead to *global* temperature decreases on the order of 2 or more degrees Celsius; and there is speculation that the largest surges could be a key factor in triggering ice ages. The latest advances in modeling the flow of glaciers have, in fact, shown that any large ice mass, including the antarctic ice sheet, can surge in certain circumstances, and a search is underway for evidence that at least some of the major glaciations started with relatively rapid rises in sea level, resulting from a hundred years or so of continuous heavy calving in one or more of the main antarctic drainage basins. This would have preceded the eventual lowering of sea level as the great continental ice sheets started building up on the Northern Hemisphere continents from the incessant precipitations of storms, anchored by the spread of the cold Southern Ocean water to the northern seas.

These are questions of profound significance for the past and future of the earth's climate, but at present they remain largely in the area of speculation. However, the icebergs of the Southern Ocean also have a very practical appeal: as a potential source of fresh water for dry coastal regions of South America and Australia. Detailed calculations show that the technical task of transporting an iceberg, measuring 200 x 900 meters, over the 3000-to-5000-kilometer distances involved is already within the capability of the world's largest operational tug, and that the cost of the delivered water would make it competitive for irrigation purposes in a large-scale commercial operation. No serious attempt has yet been made to launch such an operation, although there have been experiments in moving icebergs (Figure 13). It has been pointed out that icebergs would be the only rapidly accessible major source of fresh water for a city or region afflicted by drought if an earthquake destroyed the storage dams holding its water reserves. This is an argument for perfecting iceberg retrieval techniques so that Southern Ocean ice, a potential source of long-term climatic disasters, might be utilized to overcome short-term emergencies.

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Figure 12. Locations of icebergs from 1773 to 1960. (After Nazarov, 1962)

Figure 13. Three U.S. Navy icebreakers push a large tabular iceberg at McMurdo Sound. With the development of "super" tug boats and the use of satellites to locate iceberg fields, it is possible to transport antarctic ice to arid coastal regions. (U.S. Department of the Interior, Geological Survey)

The Southern Ocean Floor

J. R. Heirtzler

Because of its remoteness from major oceanographic centers, and because of the continuous presence of ice and adverse weather conditions, the Southern Ocean has been relatively unexplored. Yet the sea floor is known to have characteristics not found in any other ocean area.

Little information about the sea floor was obtained by early explorers of the high southern latitudes. The first significant data were acquired by researchers aboard the ships that, in more recent times, supplied the antarctic bases of various countries. Some of the better-known regions are the area immediately south of South America, the Scotia Sea, and around the Antarctic Peninsula; somewhat less known, the areas south of Australia and south of Africa; relatively little known, the high latitudes of the southern Indian and Atlantic oceans. From 1962 through 1972, the research vessel *Eltanin* was operated by the National Science Foundation across the high latitudes of the Pacific between South America and Australia, and between Australia and Antarctica. In early 1975, this same ship, renamed *Islas Orcadas* and operated jointly by NSF and the Argentine Navy's Hydrographic Office, began exploring the high latitudes of the Atlantic. *Eltanin* has done more than any other ship in providing information about the antarctic sea floor.

Early Geologic History

As with other oceans, the Southern Ocean is a product of its geologic history—a subject about which we know something today, thanks to the theory of sea-floor spreading. According to this hypothesis, the continents are moving across the face of the earth and spreading away from the center of the mid-ocean ridge system, where new material wells up from the deep earth. This spreading produces characteristic bathymetric features. Associated with the ridge axes are fracture zones; for some unknown reason, they develop at right angles to the spreading centers and point out the direction in which drift has occurred.

The sea floor adjacent to the Antarctic continent, which is older than material at the ridge axis, is thought to be 100–200 million years old, while rocks on the continent date from at least 600 million years ago. The continent is known to have been in southern polar latitudes since 200–100 m.y. ago. Before that time, in the Permian (about 250 m.y. ago), more-temperate-latitude flora grew there, suggesting that the Antarctic continent was located elsewhere.

Antarctica was the southern anchor point of the ancient supercontinent of Gondwanaland (Figure 1). It, South America, Africa, India (which was then in the Southern Hemisphere), Australia, and New Zealand were all one land mass. How these pieces fitted together has been the preoccupation of earth scientists for some time; they try to study the fractures that the subsequently drifting continents left in the sea floor, to match geologic features that were torn apart when drifting started, and to measure the magnetic latitude frozen into rocks on the continents.

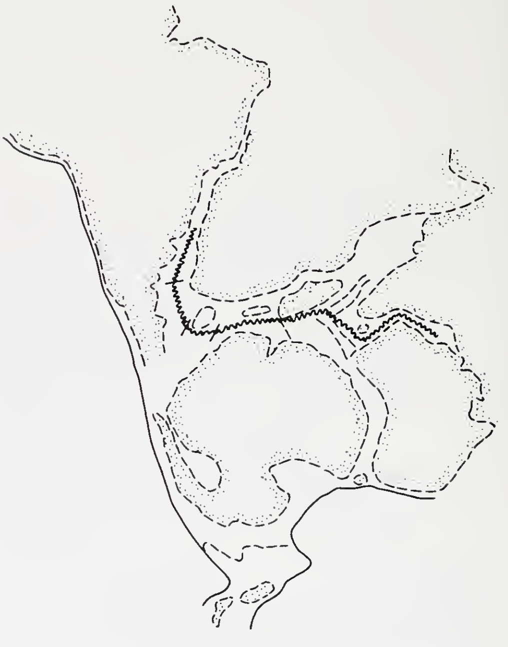

Figure 1. Fitting of Gondwanaland continents around Antarctica. Solid lines show the edge of Gondwanaland in the Triassic (200 m.y.), and broken lines portions of the continent today. Sawtooth line indicates line of first separation, all relative motions being almost at right angles to that line. (Adapted from Heirtzler, 1971)

Attempting to match geologic features and to utilize continental rocks is difficult because of the antarctic ice cover, which makes most of the land inaccessible to detailed studies of its geologic structure. With recently acquired marine geophysical data, it is possible to reconstruct the relative sequential positions of the Southern Hemisphere continents after spreading centers welled up under Gondwanaland and began to push the pieces apart. Very likely the South America–Africa combination and India, as two separate fragments, started drifting from Antarctica about 200 m.y. ago. It is believed that an initial Southern Ocean was thereby created around an antarctic continent that had the New Zealand–Australian land masses fused onto its side. New Zealand separated 60–80 m.y. ago; Australia followed about 45 m.y. ago. Because of a ridge that was dragged behind by Tasmania, the circumantarctic water route was not fully opened until the Late Oligocene—about 30 m.y. ago.

In the separation of these great land masses, fragments got scattered along the way. The most interesting and significant old land fragments are those that comprise the Scotia Arc, which forms a great bow—convex to the eastward, between southern South America and the Antarctic Peninsula—and encloses the Scotia Sea. Some earth scientists think this curved island chain was once straight north-south (Dalziel and Elliot, 1971), or lay snug against the Antarctic continent (Heirtzler, 1971). Other such fragments are the Kerguelen Plateau, largely submerged and touching the Antarctic continent in the southern Indian Ocean; the Broken Ridge, extending west from southwestern Australia; and the submerged Macquarie Ridge, south of New Zealand.

The Subantarctic Ridge System Today

The spreading centers that pushed apart the land masses of Gondwanaland, and the associated fracture zones, are still active today and are the seat of much undersea seismic activity in the Southern Hemisphere. No earthquakes have been recorded on Antarctica, but volcanic activity, which elsewhere is accompanied by earthquakes, exists at several places on the continent and the subantarctic islands. Ash from prehistoric volcanoes is a major constituent of sediments in the Pacific and Indian Ocean sectors. Doubtless there is a heat flux at the axis of the mid-ocean spreading centers.

As shown in Figure 2, the mid-ocean ridge is rather well defined and the ocean basement quite accurately dated in the Pacific Antarctic and in the Indian Ocean south of Australia. In these areas the sea floor is spreading at a rate of 2.2 to 4.5 centimeters per year. A deep-sea trench is found in the far south Pacific, off the west coast of Chile, but this trench is buried by sediments south of about 40°S. Another major trench follows the Scotia Arc just east of the island chain. The sea floor of the Southern Ocean probably is consumed (forced down into the earth's mantle) in these trenches, but the mechanism is not yet clear.

In the main part of the Indian Ocean, especially that part west of the Kerguelen Plateau (west of about 90°E), there have been few geophysical cruises at high latitudes, and the age and shape of the sea floor are still unknown.

The far south Atlantic is receiving a good deal of attention today. An active zone of sea-floor spreading has recently been found within an island arc in the Scotia Sea, and a spreading center has been discovered south of the Triple Junction.

All of these spreading centers have a very thin sediment cover (~100 m), or no cover at all. The older parts of the sea floor—those nearer the continent—generally have thicker sediments (200 km or more). Cutting through the sea floor, under the sediment cover, are the fracture zones, which represent age discontinuities. They may or may not have a ridge or scarp above them, but they can be mapped with seismic profiling techniques or by disruption of the magnetic anomaly pattern at the sea surface.

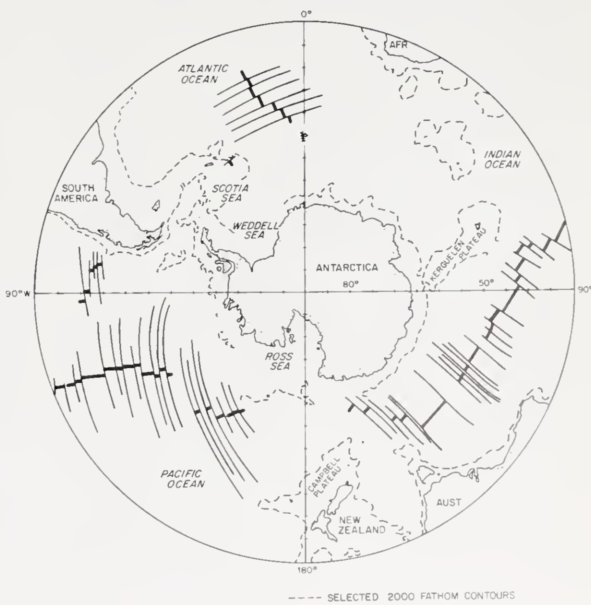

Figure 2. Known mid-ocean ridge axes (thick lines) and fracture zones (thin lines).

Sea-floor Sediments

The basic sedimentary regimes around the Antarctic continent are relatively simple (Figure 3). Close by shore, over the shelf and to a distance of some 300–600 kilometers to the north in all directions, one finds glacial marine sediments. Defined by the northern limit of pack-ice, they result from material carried from land by turbidity currents and by the many large glaciers calving into the Antarctic Ocean and being carried eastward and northward by the surface currents. The latitude range of glacial till, as recovered in deep-sea cores, has provided an estimate of the antarctic ice cover through geologic time, since the ice cover in glacial periods differed from that in interglacial times. There is evidence of extensive glaciation as early as 3 m.y. ago.

Another sediment boundary occurs at the Antarctic Convergence, where the circumpolar currents meet the relatively warmer, more northerly current system (see page 11). To the south of this area, the near-bottom water is extremely rich in radiolarians and diatoms, and the sediment is predominantly siliceous (diatomaceous) ooze. There are several major fields of manganese nodules in these latitudes, but none are of economic significance. Immediately north of the Antarctic Convergence is calcareous (mostly foraminiferal) ooze. Again, by studying the distribution of these two sediments in a deep-sea core, one may learn about the variation of the antarctic current systems during geologic time (Figure 4).

Conclusion

The areas of high South Atlantic latitudes and the area south and southeast of Africa will be of greatest interest during the next five years. The reconnaissance of the Southern Ocean will not be complete until the mid-ocean ridges and associated fracture zones have been surveyed, and until the thickness and nature of the sea-floor sediments have been studied. While this research is underway, more nationalistic surveys for offshore petroleum (see box) and minerals will continue off South Africa, Patagonia, Australia, and New Zealand.

Antarctic Oil ?

Certain geologic conditions may result in the creation of exploitable petroleum. These are (a) the existence of a dense flora in a shallow-water marine environment in the geologic past; (b) the covering of this organic material by thick layers of sediment so that the necessary chemical alterations may take place; and (c) the migration of the petroleum through porous strata and its collection in pools under non-porous caps. Sometimes the organic debris may be converted to coal or oil-bearing shale instead of oil.

Paleobotanical observations and paleomagnetic measurements show that at least sections of the Antarctic continent were at temperate latitudes in much earlier times. In fact, limited amounts of coal have been found. The paucity of geophysical observations along the antarctic coast has prohibited a comprehensive estimate of sediment volumes. The continental shelf here is unique in being somewhat deeper than other shelves, presumably due to ice-loading. Such factors may have had unusual effects on oil-producing conditions.

The *Glomar Challenger*, of the Deep Sea Drilling Project, has been able to drill a few holes on the continental shelf. Three of these, drilled in the Ross shelf area, showed gaseous hydrocarbons in strata of relatively recent (Miocene) geologic age. This gas was mostly methane, but in one case there was a trace of ethylene. (Methane is frequently found in deep-sea cores and is not considered to be an indicator of oil; ethylene often occurs with petroleum.)

Before the breakup of Gondwanaland, the Ross continental shelf was adjacent to an area in southeastern Australia that presently produces oil (Figure 3, page 31). It is tempting to believe that there might be petroleum in the matching Ross shelf area. However, the Miocene strata in which gases were found was laid down a long time after the breakup of Gondwanaland, and the presence of petroleum is by no means assured.

It was not possible for *Glomar Challenger* to drill other parts of the antarctic margin because drilling sites had not been surveyed. Thick sedimentary deposits no doubt exist on several parts of the shelf, and research ships or geophysical survey vessels will soon delineate them.—J.R.H.

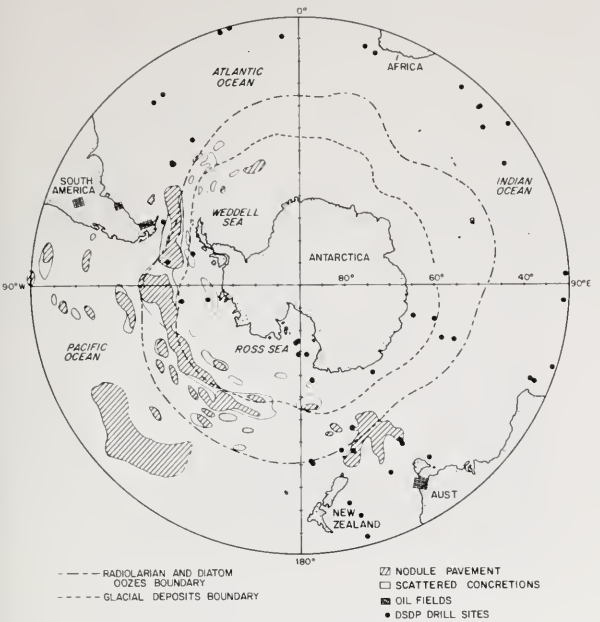

Figure 3. Glomar Challenger *drill sites, known types of sediments (after Arrhenius), and active oil fields. The northern limit of glacial erratics is shown by the dashed line; and the Antarctic Convergence, which separates the northern calcareous ooze from the radiolarian/diatom zone, is shown by the dot-dashed line. The distribution of manganese in the South Atlantic–African sectors has not been studied.*

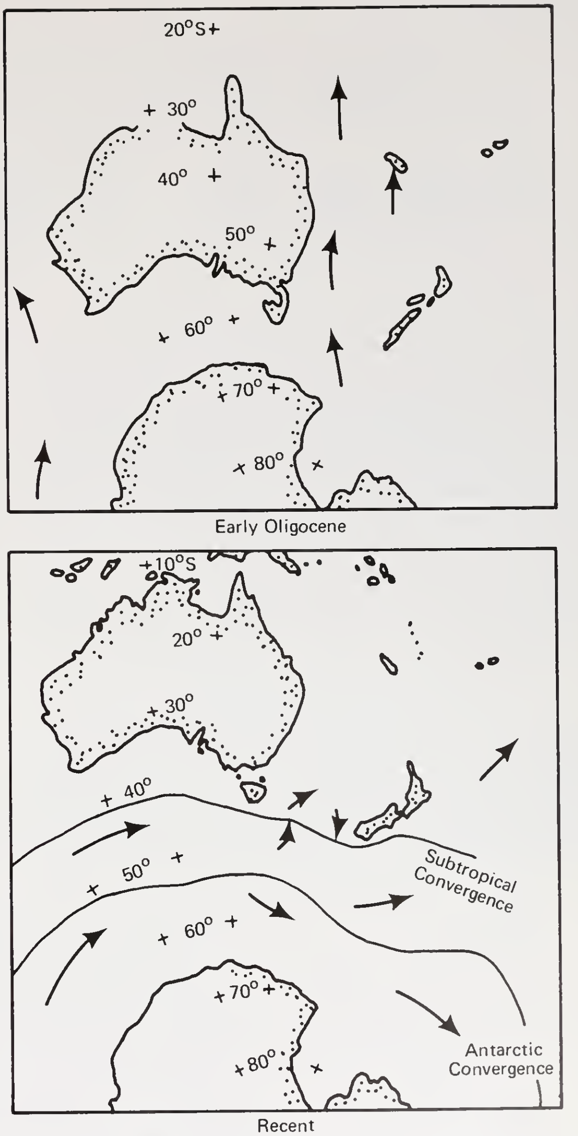

Figure 4. Change in current flow south of Australia from Early Oligocene (37 m.y.) until present. (Adapted from Kennett, 1974)

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Operating in Antarctic Waters

Guy G. Guthridge

Caution.—*The mariner must employ great care in navigating the regions covered by this volume. Very few of the bays or harbors have been thoroughly surveyed. Information contained herein was compiled from numerous sources, much of which appears to be contradictory. Charts of the antarctic region lack details, and should be utilized only as a guide. Mariners should not place too great reliance upon sketchy reports of observers, since the unusual atmospheric conditions in the south polar regions often lead the inexperienced observer to optical illusions.* *

Icebergs, sea ice, cold, and wind frustrate and sometimes prevent oceanic research in the southern latitudes—the roaring forties, the furious fifties, and the screaming sixties. The Circumpolar Current and persistent westerly winds whip antarctic waters into the world's stormiest. Sea ice, whose winter growth doubles the ice area of Antarctica, prohibits access to vast regions (see Figure 10, page 25).

Despite these obstacles, research and supply ships routinely penetrate the pack-ice and reach open waters adjacent to the continent (Figure 1).

The difficulty of shipboard research generally increases as one travels southward. Beginning at about 60°S, the first hazards encountered, in addition to fierce storms, are ship icing (Figure 2) and icebergs (Figure 3). Most of the icebergs are tabular, having calved from floating ice shelves adjacent to the continent. Farther south, so-called ice-strengthened ships (stronger hulled than normal ships but not as strong or as powerful as icebreakers) can enter pancake ice (see Figure 8, page 23) or loose pack (Figure 4). A.R.A. *Islas Orcadas,* formerly U.S.N.S. *Eltanin,* and R/V *Hero* are examples of ice-strengthened ships.

In denser pack, only an icebreaker will do. Although their primary function is to open a path for thinner-hulled ships (Figure 5), icebreakers are used regularly as research platforms. Special facilities aboard U.S.C.G.C. *Glacier,* for example, include chemical, biological, geological, hydrographic, and photographic laboratories, and data processing equipment for the evaluation of scientific information. Most icebreakers carry helicopters for ice reconnaissance, transport services, and such work as seal census taking; also, there are boats for transport work and collecting scientific samples (Figures 6 and 7).

A sudden shift in weather can render helpless the most powerful icebreakers (Figure 8). Then, the best thing those aboard the beset ship can do is relax; in a few hours, or days, or perhaps weeks, the wind will shift again, and open waters will replace pressure ridges.

Sailing Directions for Antarctica, H.O. Pub. 27, U.S. Naval Oceanographic Office, 1960, p. 1.

Guy G. Guthridge is director of the Polar Information Service, Office of Polar Programs, National Science Foundation.

Figure 1. The National Science Foundation research ship Hero, *38 meters long and ice-strengthened, operates along the west coast of the Antarctic Peninsula at about 64°S. (William R. Curtsinger)*

Figure 2. At about 60^{o}S, between South America and New Zealand, Eltanin *encountered icing in 1964 during Cruise 13. Icing can interfere with scientific work by clogging instruments and making decks hazardous. (Arno Kosko)*

Figure 3. Tabular iceberg. Bergs have been seen as large as 160 kilometers on a side. (U.S. Coast Guard)

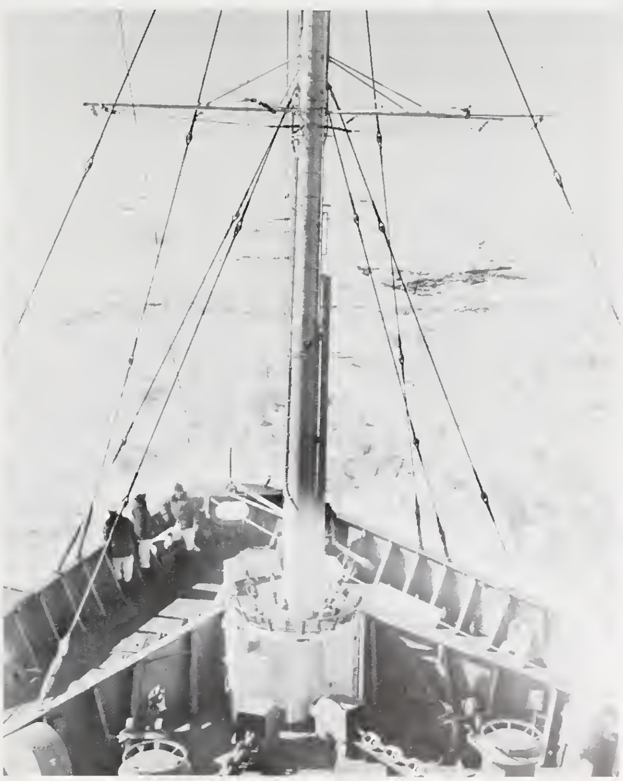


Figure 4. Typical consolidated pack-ice.

Figure 5. Two U.S. Coast Guard Wind-*class icebreakers open a channel through McMurdo Sound to the largest U.S. antarctic station, McMurdo, at the southern tip of Ross Island. (U.S. Navy)*

Figure 6. U.S.C.G.C. Burton Island *in the Ross Sea with two HH-52A helicopters, her usual complement. (Official U.S. Navy photo by PH2 John Carnevale)*

Figure 7. U.S.C.G.C. Southwind's *boat transports scientists to a floe in the Amundsen Sea during census taking of seals, whales, and birds in early 1972. The ship penetrated as far south as 72° 30′S. (Official U.S. Navy photo by PH1 Milt Putnam)*

Figure 8. U.S.C.G.C. Glacier, *the largest U.S. icebreaker, beset in Antarctic Sound (63° 20′ S) at the tip of the Antarctic Peninsula in March 1975.* Glacier *was trying to rescue the Argentine icebreaker* General San Martín, *also beset. The U.S. ship was trapped for 9 days before an unexpected gale freed her on March 11. The* San Martín *remained trapped until March 26. (Lt. R. M. McAllister, U.S. Coast Guard)*

Geochemistry
of the Circumpolar Current

John M. Edmond

New ice under light pressure. (A. W. Erickson)

The Antarctic Circumpolar Current is a unique feature in the world's oceans. Driven by the strong westerly winds of the Southern Ocean, it circles the globe from west to east at approximately 50° south latitude. The current appears to extend to the bottom everywhere along its track, resulting in an immense volume transport in the region of about 200 million cubic meters per second. The effect of the wind is also to drive the surface water northeastward, which creates extensive upwelling of water from deeper levels close to the continent. At very high southern latitudes this effect is accentuated by the action of prevailing easterlies. The divergence in flow of the surface waters in the transition zone between these two wind systems is the region of most intense vertical motions in the water column (see Figure 7, page 15).

At about 45°S the northward drift of surface water encounters warmer water moving southward from temperate latitudes, and a pronounced frontal system is developed–a region where the surface temperature changes by several degrees in a few kilometers. Associated with this Circumpolar Front is intense mixing of the two water types. The resulting mixture is still sufficiently cold, and therefore dense, so that it sinks below the warmer water and propagates northward at a depth of around 900 meters. This Antarctic Intermediate Water can be traced at least as far as the equator in all the oceans, and there is evidence of its penetration into the Carribean and of its presence in the Gulf Stream as far north as Cape Cod.

The depth of propagation of the intermediate water is determined by its density and by the vertical stratification that, in time, is controlled by the presence of other denser waters. Original antarctic surface waters, while quite cold (less than 4°C), are of relatively low salinity (~34.0%) because of the large excess of precipitation (100 cm) over evaporation (50 cm). Their mixture with the warmer, more saline northern waters gives a water mass of intermediate density. In restricted areas close to the continent, however, the surface waters not only are cooled to the freezing point (-1.87°C) but also have their salinity increased by the freezing out of fresh water as pack-ice. In the Weddell and Ross seas then, this icy, salty water cascades down the continental slope, from the large embayments where it is formed, to abyssal depths. Again, a major water type (Antarctic Bottom Water) is produced that can be traced to the northernmost latitudes of all the oceans. It is clear that the

processes going on in the Antarctic Circumpolar Current serve to "ventilate" the deep seas: the system acts as a giant lung.

Oceanic Layers

The importance of this system to geochemists lies in the analogy between it and the lung. Almost everywhere in the ocean, the water column is divided into two layers. The upper is shallow and vertically well mixed. It responds to local climate and thus is hot and salty in the tropics, cold and dilute at high latitudes. It floats on the great mass of cold and salty water that is the oceanic interior. As implied by the idea of floating, the boundary between the two layers is a zone of high vertical gradients in the density. This pycnocline acts as a firm barrier to mixing between the two layers, which are almost (but not quite) incommunicado.

Fortuitously, the maximum depth of penetration of sunlight coincides with the upper part of the pycnocline. Phytosynthesis, hence the primary production of organisms, is therefore restricted to this upper, shallow layer. However, the remains of dead organisms—their tissues, carapaces, and other hard parts—sink across the mixing barrier. In the interior of the ocean this rain of organic debris is metabolized by bacteria and higher organisms and regenerated in soluble form. Thus, the surface ocean, which has the light energy available for biological productivity, is starved of the nutrients essential for life, while the dark, cold abyss is enriched. The Circumpolar Current is one of the few places where this dichotomy is resolved: the deep, nutrient-rich waters upwell, under the action of the wind, into the photic zone. The resulting biological productivity is enormous. Indeed, the limiting factor to growth at these high latitudes is not nutrients but light. The Circumpolar Current is of central importance in being, in fact, the major site of communication between surface and deep oceanic layers.

The Current as a Laboratory

The region has added geochemical significance in that it acts as a natural laboratory. If the oceans were in chemical equilibrium, laboratory and armchair (or better, computer) chemistry would be sufficient for their description and understanding. However, while chemical transformations tend to the equilibrium or lowest energy state, these transformations themselves require energy to get going—this is the role of the lighted match in the gas-filled room.

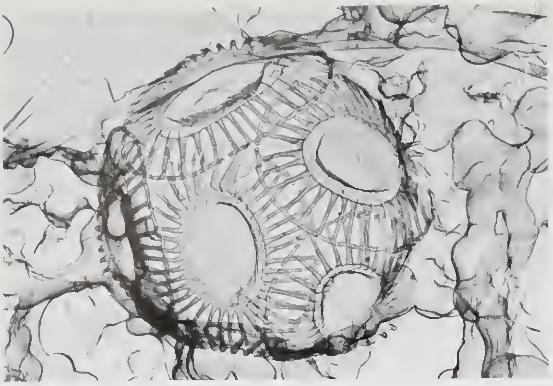
Slow kinetics greatly complicate the study of most natural chemical systems. One of the major culprits is organisms. The ability of plants, for example, to tap and store solar energy allows them to completely circumvent the environmental restrictions on possible chemical processes. As mentioned above, organisms are a very important chemical agent in the ocean; they dominate the chemistry of not only the obvious things like essential nutrients but also the more bizarre species such as copper, barium, and even radium.

The net result of the various disequilibrium processes cannot be predicted. One cannot manipulate the oceans as one does a test tube or a reaction flask. The traditional experimental approach to science is to control the important variables explicitly and then determine the effects of systematic individual changes in these on the system being studied. The ocean can be thought of as a dynamic laboratory within which the variables themselves change continuously in space (although, one hopes, not in time). To do an experiment, the researcher must find a place where one or another of the variables is dominant so that its effects can be uniquely interpreted. As might be expected from the above discussion, the Circumpolar Current is an interesting corner of the oceanic laboratory.

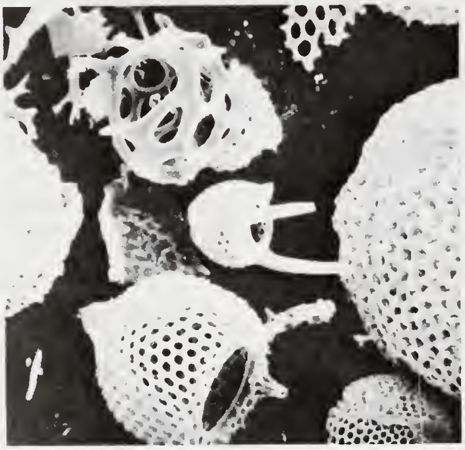
Upwelling and Water-Mass Formation

Experiments that can be performed in the Southern Ocean relate to upwelling processes and water-mass formation. Since the fundamental task of marine geochemistry is to decode the record of the oceanic environment contained in deep-sea sediments, the results of these experiments must be related to the observed types of sediments in the region and the time-stability of the system examined.

The first-order question about the upwelled water concerns the degree to which it is affected during its sojourn at the surface before it descends again to intermediate and abyssal depths. How efficient is the lung? For the dissolved gases it depends: oxygen, depleted in the deep sea by the metabolic processes involved in nutrient regeneration, exchanges rapidly with the atmosphere and, save in very "young" patches of upwelled water, is close to saturation; carbon dioxide exchanges slowly since it forms a hydrate, carbonic acid, by reaction with water. The back-reaction is slow, indeed in our own lungs we have an enzyme that catalyzes the reaction so that ventilation can proceed at a useful pace. The upwelled waters are supersaturated with carbon dioxide derived from the metabolized organic remains. It would appear that atmospheric



(Top) Transmission electron micrograph of the coccolithophorid alga Emeliania huxleyi *at 8800x magnification. (Bottom) Scanning electron micrograph of planktonic foraminifera (left and right) and radiolarians (center)at 156x magnification. (Susumu Honjo)*



equilibrium is not achieved in the lifetime of the surface waters (two years at most). Furthermore, equilibrium with atmospheric radiocarbon is not reached, and the sinking waters look anomalously "old."

Nutrients are taken up and removed from the system to varying degrees. Silica is removed by diatoms about twice as fast as nitrate, and carbonate is depleted only to a minor extent. This is due to the fact that the Circumpolar Front represents a major faunal boundary: north of it, organisms that secrete carbonate shells—coccolithophorids, foraminifera, and pteropods—are abundant; south of it, opaline organisms, especially diatoms, are the dominant species. Antarctica is therefore ringed with a series of sediment types: glacial debris close to the continent carried out in icebergs and dumped as they melt; then diatomite; and finally, beyond the frontal boundary, calcareous material (see page 30). The total nutrient depletion relative to the upwelled waters is less than 25 percent.

Sinking antarctic water masses have a distinctive "chemical signature"—high oxygen levels and intermediate concentrations of nutrients—that makes them easy to trace. The only other significant water masses in the deep ocean form in the North Atlantic from low-latitude surface waters driven north in the Gulf Stream and associated currents, and they are therefore very high in salinity and extremely low in nutrients. It is rather as if the various cores of propagating waters were color coded. The colors dissipate with intermixing and also "fade" due to the addition of regenerated carbon and nutrients, which blur the initial contrasts.

Glacier moving seaward, Balleny Islands. (A. W. Erickson)

This diversity in chemical properties of the various water masses makes identification of local chemical processes in the ocean very difficult in that they are imposed on a high and variable background maintained by physical processes—currents and mixing—rather than instantaneous chemical effects. A major control on the distribution and variability of dissolved species in the oceans is the peculiar chemical signature of the antarctic water masses.

Pollution

The Circumpolar Current has received much additional attention recently because of its location far from sources of anthropogenic pollution. Pollution, in the form of wholesale extermination of the enormous populations of marine mammals, has, of course, been "exported" to the region over the last 150 years. However, it is the atmospherically transported materials such as DDT, radioactive fallout, and heavy metals that are presently entering the area (see page 45).

The industrialized world, and its associated effluents, is confined almost totally to the Northern Hemisphere. Large-scale dynamics of the oceanic and atmospheric circulations are such that exchange

between the hemispheres is slow. There is therefore a lag in time between the introduction of "new" pollutants such as DDT or PCB to the environment and their penetration to the far south. In the case of the bomb-produced radioisotopes C-14 (radiocarbon) and H-3 (tritium), this effect is quite pronounced. Both isotopes are concentrated rapidly in the ocean in the forms of CO_2 and H_2O, respectively. Scavenging of tritium from the atmosphere in rain is especially efficient. Consequently, the great proportion of these isotopes entered the oceans of the Northern Hemisphere, and only a minor component has survived to contaminate the Antarctic. The same general picture holds for industrial pollutants. Pronounced hemispherical gradients have been observed for carbon monoxide and Freon. Concentrations of DDT in organisms generally decrease southward, although trace levels have been detected in penguins and seals from the Antarctic continent.

Though remote and isolated, the Antarctic is affected by the effluents of industrial society. Trace levels of DDT, for example, have been found in the fatty tissues of Adélie penguins and crabeater seals. (H. Armstrong Roberts; A. W. Erickson)

Since the Southern Ocean is far removed from all pollution sources, accumulation rates of industrial effluents should be quite uniform since the effect of the strongly heterogeneous distribution of the sources has been "smeared" by distance. This is not true for the Northern Hemisphere, where local effects can severely interfere with attempts at background measurement. A number of monitoring experiments are now underway both on antarctic islands and on the continent itself in an effort to determine the global response to the chemical perturbations of industrial society.

Conclusion

The role of the Circumpolar Current as a natural laboratory is only beginning to be explored; much systematic reconnaissance remains to be done. It is especially important to establish the magnitude and importance of seasonal variation in the rates of upwelling, water mass formation, and surface productivity. The pronounced latitudinal variations in faunal distribution must result in large differences in the amounts and composition of particulate material transported across the thermocline. The consequences of this should be studied in detail.

Oceanographic work in the Circumpolar Current is the most difficult and expensive of all, owing to the great distances involved and to the extreme weather conditions. The potential rewards more than justify the efforts.

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Standing almost four feet tall, the emperor is the largest of all penguins. It breeds on the antarctic ice and carries its single egg on its feet. (Harold M. Lambert)

Biology of the Southern Ocean

Sayed Z. El-Sayed

Biological exploration of the antarctic seas antedates, by some 30 years, the era of modern oceanography ushered in by the *Challenger* expedition (1872-76). For it was during the voyage of H.M.S. *Erebus* and *Terror* (1839-43), under Sir James Clark Ross, that four species of fish were collected off Iles de Kerguelen, and plankton samples were taken by J. D. Hooker, the famed botanist-surgeon of that expedition. The plankton samples were sent to the German diatomist Ehrenberg, who published in 1844 the first paper on antarctic diatoms.

Following the *Challenger* expedition (when nine more species of fish were caught off Kerguelen), and *Belgica* (1897-99)–the first ship to collect fishes within the Antarctic Circle–there was a spate of international expeditions from about the turn of the century to the outbreak of World War II. Among the celebrated voyages to the Southern Ocean during this period are those of *Terra Nova, Antarctic, Southern Cross, Scotia, Valdivia, Pourquoi Pas?, Gauss,* and *Meteor.* Although these expeditions gathered significant information on the area, it was not until the initiation of the *Discovery* investigations (1925-37) that the foundation of our knowledge of the physical, chemical, and biological oceanography of the Southern Ocean was firmly established.

Biological exploration of the antarctic seas remained in a hiatus during and immediately following World War II. But thanks to the Soviet investigations on board *Ob* in the late 1950s (during the International Geophysical Year) and the U.S. efforts on *Eltanin* in the 1960s, the momentum of antarctic research was renewed.

The knowledge accumulated from antarctic investigations showed that, in marked contrast to the barren and hostile continent, the surrounding seas are bountiful and hospitable. Their nutrient-rich waters support a wealth of plant and invertebrate-animal life on which large populations of penguins, fishes, sea birds, seals, and whales depend for their living. These antarctic organisms were found to share some unique features that set them apart from those more familiar to scientists in tropical and temperate waters: for instance, large body size, slow growth, and small number of species. They were also found to be

remarkably well adapted to the severe environmental conditions in which they live.

It is in response to the physical/chemical environment and, in particular, to the high oscillations of some of the environmental parameters that the antarctic organisms have developed their characteristic features. For example, the marked seasonal changes in the polar regions, together with the short period available for plant growth, may be more significant in determining species-poverty than are the low temperatures to which many organisms seem to be fairly well adapted. Another factor helping to shape the character of antarctic biota and contributing to the high level of endemism is the geographical and climatological isolation of the continent and its surrounding seas from the rest of the world. The closest land mass (South America) is nearly 800 kilometers from the South Shetland Islands, and New Zealand and South Africa lie about 2000 and 3500 kilometers, respectively, from the continent.

Before discussing the various components of the marine biota, it is important to present a brief account of the physical and chemical features of the Southern Ocean (see also pages 8 and 36).

Water Masses and Ocean Circulation

The almost circular outline of the ice-covered Antarctic continent, except for the deep indentations of the Weddell and Ross seas, is surrounded by essentially concentric rings of water masses whose surface currents have contributed to the isolation of the continent. Under the influence of prevailing westerly winds, the surface waters move eastward in a clockwise direction (see Figure 1, page 10). Superimposed on this eastward circumpolar movement are north-south components.

At its northern limit the Antarctic Surface Water sinks beneath the less-dense Subantarctic Surface Water. The region where the sinking occurs is referred to as the Antarctic Convergence, or Polar Front (see Figure 7, page 15). The principal feature by which the convergence is located is a steep temperature gradient at the sea surface. Marked increase in nutrient salt concentrations is also quite noticeable south of the convergence; as a result of this increase, the region to the south is, in general, much richer and more productive than the Subantarctic Surface Water to the north. The Antarctic Convergence seems to have a marked influence on the distribution of phytoplankton, zooplankton, fishes, and birds.

At the edge of the continent, the very cold water sinks, forming Antarctic Bottom Water, which moves northward along the narrow shelf and into the deep, then fans out into the Atlantic, Pacific, and Indian oceans. Above the bottom water lies the relatively warmer, more saline, and nutrient-rich south-flowing Circumpolar Deep Water. The upward movement of this water creates a zone of upwelling, supplying to the surface water vast quantities of nutrients that contribute to the luxuriant growth of phytoplankton and other marine life close to the coasts of Antarctica (see page 37).

The development of fast-ice (near the continent) and pack-ice (south of the Antarctic Convergence) has a profound influence on the antarctic ecosystem. The area covered with pack-ice undergoes seasonal fluctuations; it is reduced from 24 million square kilometers in September to 18 million square kilometers in February. Throughout its cycle of waxing and waning, this circumantarctic ice belt is moving from east to west, and with it are the multitudes of marine organisms that inhabit the pack-ice zone. Thus, on the basis of ice distribution, we can recognize three concentric zonations: the fast-ice zone, the open waters, and the pack-ice zone (see page 22).

Biota

Phytoplankton

Diatoms are the dominant component in antarctic phytoplankton, next the dinoflagellates and silicoflagellates. Nearly 100 species of diatoms have been found in antarctic waters, with more than 60 species of dinoflagellates and only one species of silicoflagellates. Endemism is rather high, reaching nearly 80 percent in the dinoflagellates.

Our knowledge of the distribution and ecology of phytoplankton has substantially increased thanks to the extensive investigations carried out by the late J. T. Hart of *Discovery* and, more recently, by Soviet and U.S. scientists. As a result of these investigations, we know that there are discernible geographic and seasonal variations in the distribution of the standing crop (biomass per unit area or volume) and primary production. Large biomasses are found in the Scotia Sea, west of the Antarctic Peninsula, in the Ross Sea, and in the southwestern Weddell Sea. The extensive studies conducted by Texas A&M investigators during the past twelve years in the Atlantic, Pacific, and southeastern Indian sectors of the Antarctic and Subantarctic have shown that there are conspicuous regional differences in the standing crop and primary productivity in these regions. Their investigations have clearly demonstrated that the high productivity of antarctic waters is factual only with regard to

the inshore waters, and not with respect to the oceanic regions. These observations, together with the recognition that the productive season in antarctic seas is about 120 days per year, are now forcing scientists to qualify earlier emphasis on the extreme productivity of the Antarctic Ocean.

Zooplankton

Extensive studies made by the *Discovery* investigations have added a wealth of knowledge about the composition, distribution, and life histories of the most dominant zooplankton species. However, information is still lacking with respect to standing stock estimates and food web relationships. Although most, if not all, zooplankton species are circumpolar in distribution, they frequently show centers of concentration at different depths or in different latitudes. The circumpolar distribution of many plankton species seems to be lopsided, with large populations in the Scotia/Weddell Sea region and thinner bands around the rest of the continent. As with the phytoplankton stocks, antarctic waters south of the convergence are richer in zooplankton than subantarctic waters to the north. Southern Ocean zooplankton also exhibit seasonal variations: in summer, they are much more plentiful in coastal than in open-ocean waters; in winter, they are found at greater depths.

The dominant organisms in antarctic zooplankton are the copepods and the euphasiids; in the past the latter have supported enormous stocks of whales (Figure 1). Euphausiids show zonation according to the various species: north of the Antarctic Convergence is *Euphausia valentini;* in the pack-ice, *E. crystallorophias;* and in open waters south of the convergence, dense patches of the larger species *E. frigida* and *E. superba.* Although the largest concentrations of *E. superba* (krill) are in the Atlantic sector, they are very unevenly distributed and tend to congregate in large swarms

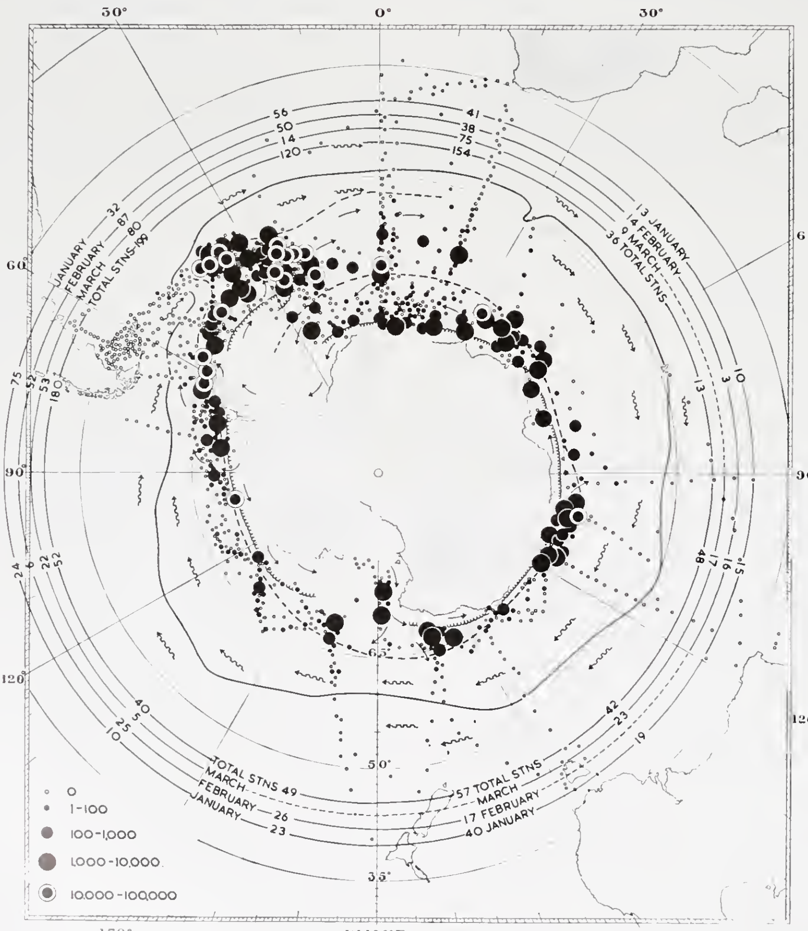


Figure 1. Distribution of staple whale food in summer. Ice-edge February mean. (After Marr, 1962)

of a single age-class. The swarming habit greatly facilitates the baleen whales' feeding on these animals, with blue whales preferring adolescent krill and fin whales favoring the adults. These swarms average 40 x 60 meters in size; maximum dimension recorded for a swarm is 600 meters. They can be dense enough to discolor sea water and can therefore be easily spotted from the deck of a ship or by remote sensing from satellites. In recent years the antarctic krill has been the focus of much international attention and will soon be the object of commercial exploitation by many countries, as will be discussed later.

Fishes

Although inventory of antarctic fishes is relatively complete, our knowledge of the distribution and biology of these fishes is still fragmentary. Nearly 75 of the 90-100 species of antarctic benthic fishes belong to the group Nototheniiformes, most of which are sluggish bottom dwellers, with large heads and tapering bodies. As a group, they are highly diversified in structure, habit, and distribution. Although antarctic bottom fishes can be locally important in coastal regions, they are usually insignificant in the Southern Ocean because the narrow continental shelf surrounding the continent limits the abundance and spawning sites of these bottom dwellers. Investigators have reported very few fish eggs and larvae in plankton net hauls. Some southern fish species seem to have overcome the problem of lack of spawning sites by spawning in the coastal waters of the subantarctic or on the continental shelf of Patagonia, then assuming a pelagic existence as adults (Laws, 1974).

Endemism is high among antarctic fishes. It has been estimated that if all the deep-sea, coastal, and associated pelagic forms are considered, about 80 percent of the species found in the Antarctic have not been encountered elsewhere. The reason for this unusually high degree of endemism is the physical isolation of the Antarctic continent and its associated islands from the rest of the world—an isolation that has been in effect for nearly 65 million years.

There are no reliable estimates of the stocks, biomass, or productivity of antarctic fishes. Although the Soviets are now marketing *Notothenia rossi* in Moscow, Leningrad, and other Russian cities, it is difficult to guess the magnitude of this or any other fish stock in the Antarctic. Our knowledge is also deficient on the autecology of most fishes in this region. Their remarkable adaptation to temperatures below the natural freezing points of their body fluids has recently begun to attract considerable attention. The "antifreeze protein" (glycoprotein) isolated from *Trematomus borchgrevinki* may be useful as a refrigerant for red blood cells, sperm, and tissue. The study of adaptation to extreme polar conditions in fish and other mammals is among the most fascinating and promising in antarctic biology.

Birds

The study of antarctic birds has a rich history dating back to the early exploration of the region. They are among the well-documented animal groups; taxonomic and biogeographic studies have, until recently, dominated investigations.

Nearly all the 50 species of birds that breed on the islands, or around the continent, derive their food either directly from the sea or one step removed from it. Their distribution is limited by such environmental factors as restricted sites for breeding and nesting, low temperatures and high winds, and availability of food. Because the annual cycles of these birds are closely linked to food abundance, their breeding seasons are short and well timed. Oceanic birds seem to depend on krill and, to a lesser extent, squid and fish.

In recent years research on the ecology and population dynamics of antarctic birds has gained momentum, and studies have begun on their physiology. However, quantitative biological research is extremely difficult, and census data for bird populations at sea are virtually nonexistent, or poor estimates at best. Nevertheless, it is safe to assume that the avian population constitutes a very small biomass in the Southern Ocean.

Benthos

In the Antarctic, ice phenomena are the dominating influences on the shallow (0-33 meters) environment. The ice-scoured antarctic littoral and upper sublittoral zones are relatively barren. Intertidal algae are absent from regions where the shore is covered with ice for extended periods; however, there is a well-developed algal belt below extreme low tide.

The physical characteristics of the environment are relatively critical to the distribution and abundance of the benthic fauna. Studies of the benthic communities in McMurdo Sound showed that physical stresses have resulted in a vertical zonation of the dominant sessile organisms (Figure 2). With increasing physical stability, the macroscopic epifauna, and presumably the microscopic infauna as well, become more abundant and diverse, and biological interaction becomes more obvious.

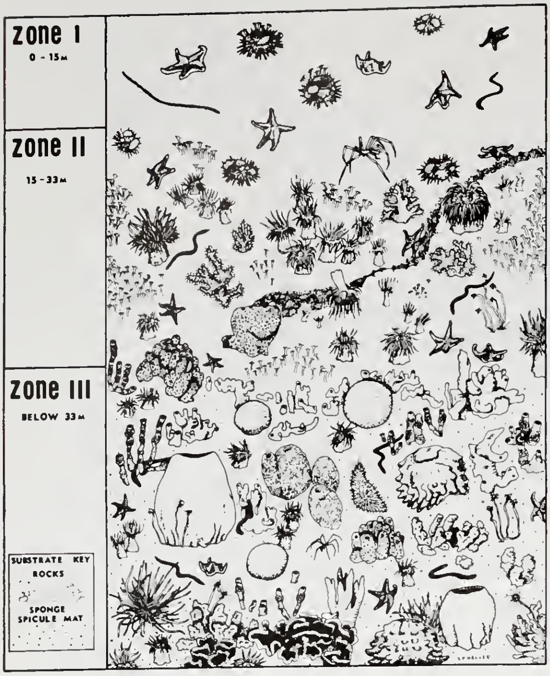


Figure 2. Zonation of dominant sessile organisms at McMurdo Sound. (After Dayton et. al., 1970)

Most of the published quantitative data on the standing crop of antarctic benthos come from the pioneering efforts of the Russian investigators. At comparable depths, especially in depths below 200 meters, the average biomass is from several times to an order of magnitude greater in the Antarctic than in the Arctic. At about 500 meters in the Davis Sea, the benthic biomass is comparable to that in the Bering Sea, while at depths of 1000 meters and less, the average values are greater in the Bering Sea. Russian scientists have estimated that as much as 60 percent of the standing crop of benthos may not be directly available as food for other organisms. However, recent studies pointed out the fallacy of the long-held belief that the large, slow-growing sponges and colonial polyzoa of the antarctic sublittoral zone are the dead-ends in the food chain. There is now evidence to show that they are recycled in the general web of life.

Whales

The great abundance of marine mammals in the Southern Ocean has provided the main stimulus for the exploration of the continent and its surrounding waters. Antarctic seas are frequented by six species of baleen whales (blue, fin, sei, humpback, minke, and southern right whale), and one toothed species (sperm whale). Stocks of these whales were probably far greater than in any other ocean and have long sustained the southern whale industry.

A century ago, the initial numbers of baleen whales feeding in antarctic waters totaled about one million, with a biomass of about 43 million metric tons. By the 1930s the population was reduced to about 340,000. The current biomass is about one-seventh of the initial stock, or roughly 6.2 million tons. Total annual catch of baleen whales is presently between 1.5 and 1.7 million tons.

Krill is the most important food of baleen whales, although other euphausiids and copepods are also consumed. Nemoto (1970) has shown that blue whales feed mainly on euphausiids, fin whales on both euphausiids and copepods, and sei whales primarily on copepods. The preference of whales for food organisms must have affected cetacean distribution and abundance. Although the amount of food consumed by the whales is not known, Mackintosh (1970) suggested that an adult whale may consume several times (between 1.5 and 15) its own weight annually, and Moiseev (1970) estimated that annual consumption of krill by the whales is on the order of 140 million tons. The reduction of whale populations during the past 40 years has led to the belief that there must have been an increase of krill and of the animals that feed on krill. However, evidence for such an increase is poor (Gulland, 1974).

Seals

Of the six pinniped species found in the Southern Ocean the crabeater, Weddell, leopard, and Ross seals may be considered truly antarctic, since their life cycles show strong association with the fast-ice and pack-ice surrounding the continent. The other two species, the southern elephant seal and the southern fur seal, are also common to the area.

Food preference and feeding habits seem to have greatly influenced geographical distributions of antarctic seals. The crabeater seal and the fur seal feed primarily on krill. The former is restricted to the fringes of the pack-ice zone, and the latter is limited to the region bounded on the south by the pack-ice edge and on the north by the Antarctic Convergence. The crabeater seal is believed to be the most abundant pinniped in the world, with a population density on the order of 30 million seals.

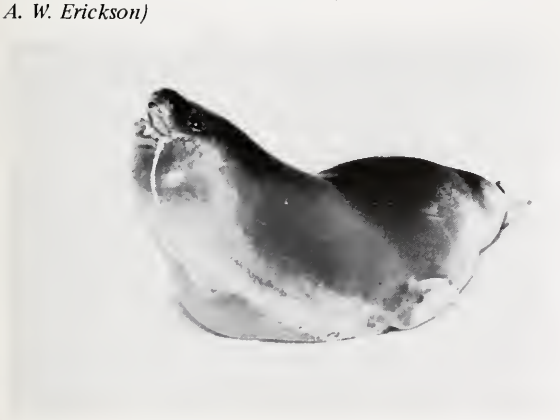
The Weddell seal, which is predominantly a fish eater (and occasionally feeds on squid, decapods, crustaceans, amphipods, and euphausiids), inhabits the inshore fast-ice. Its remarkable ability to maintain breathing holes in the ice has extended its range of distribution to include habitats not available to other seals. However, the accompanying tooth wear has contributed to the high mortality of the adults. It is estimated that the total Weddell

seal population is between 200,000 and 500,000 individuals, and may even be much higher.

Largest of antarctic seals is the solitary and widely dispersed leopard seal. It feeds on krill, fish and, occasionally, penguins, making it the only seal that feeds on warm-blooded animals. Although it has a wider range than other seals, it is usually found at the fringe of the pack-ice. Recent census data indicate that the leopards comprise about 3 percent of the seals found in pack-ice areas, suggesting a population several times larger than the original estimate of 200,000 to 300,000.

The least-known and rarest antarctic seal is the Ross, with fewer than 50 sightings reported prior to 1945. It has a circumpolar distribution, with localized concentrations. The total Ross seal population is probably at least 100,000, and may be higher (Hofman et al., 1973), which represents 1-2 percent of the total antarctic pinniped population.

The Weddell seal (top) maintains breathing holes in the antarctic ice, greatly extending its range of distribution. Because it inhabits the fast-ice near shore, the Weddell seal is one of the most thoroughly studied mammals of the Antarctic. In contrast, the Ross seal (below) is rare and not often seen, preferring the hard-packed ice where ships and men are unlikely to penetrate. (H. Armstrong Roberts; A. W. Erickson)



A skua with its chick. Residues of DDT have been detected in several species of antarctic birds, including the skua. (H. Armstrong Roberts)

Food Relationships

Sufficient information has now accumulated from various expeditions to allow us to draw a fairly reasonable picture of the food chain relationship in antarctic waters. Shown in Figure 3 is the food relation in the open water, and in Figure 4 that in the pack-ice zone. The two figures illustrate the significant role of krill in the trophic relationship in both ecosystems.

Pollution and Overexploitation

The short and simple marine food chain in the Antarctic, diatoms→krill→whales, is well known. The simplicity of the system makes it more vulnerable to outside disturbances than the more complex and stable ecosystems encountered in tropical and subtropical waters. Its vulnerability is now being tested under the strain of two man-made factors: the commercial exploitation of the mammalian populations, and the influence of toxic chemicals introduced from the industrial regions to the north. With regard to the former, there can be no doubt that the antarctic marine ecosystem has been significantly influenced by man's exploitation of baleen whales. The disastrous decline in these stocks is well known and well documented. The other less-known factor of environmental pollution deserves further examination here (see also page 38).

The remoteness of the continent, its isolation from the rest of the world by the vast expanse of surrounding ocean, and its lack of indigenous human population are among the factors contributing to the comfortable belief that Antarctica would somehow remain unspoiled and uncontaminated. However, in recent years there is

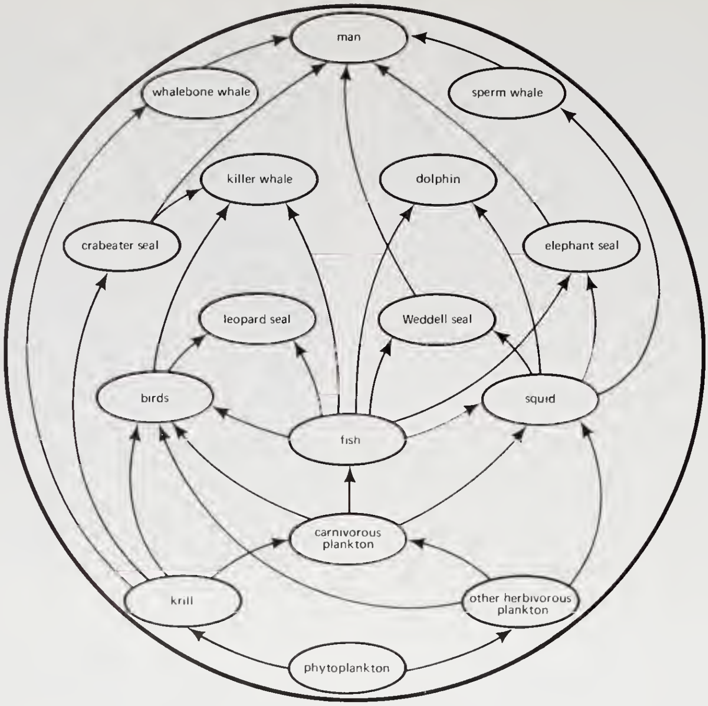


Figure 3. Food chains in the open sea. (After Hart, 1942)

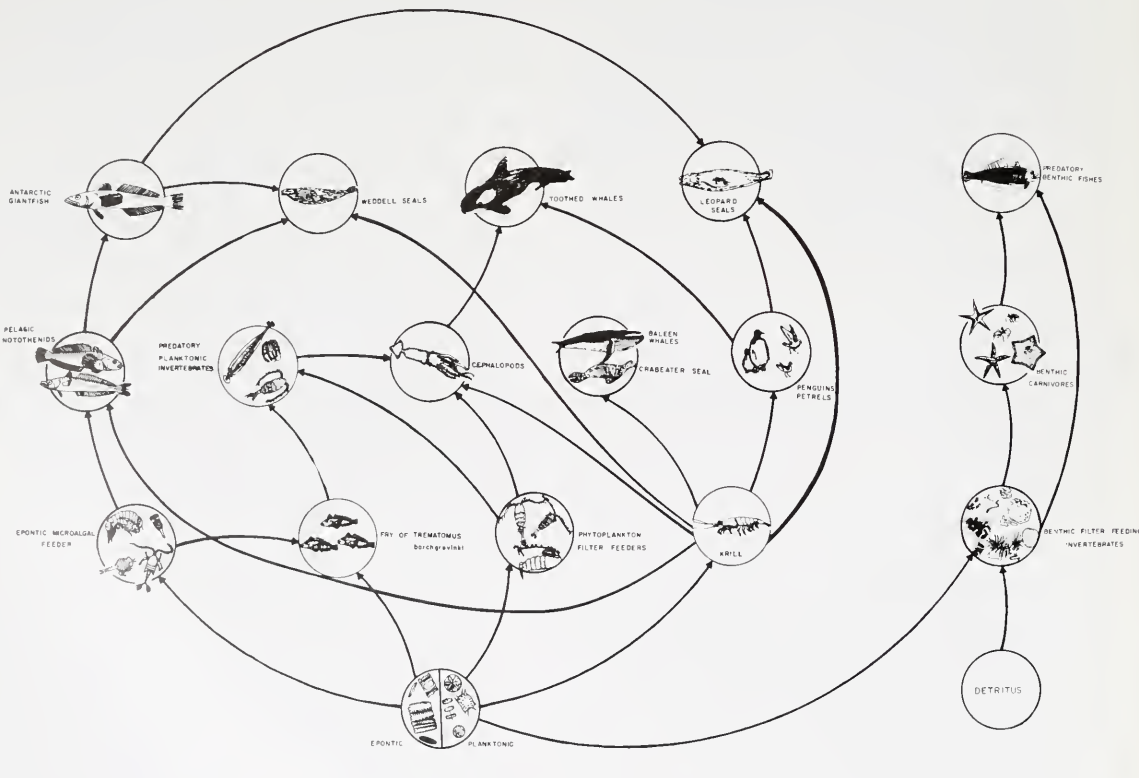


Figure 4. Food chain relationships in the pack-ice zone. (After El-Sayed, 1970)

disturbing evidence that this once "pristine" environment is being subjected to the curses wrought by modern technology.

In 1966 Sladen and his colleagues first reported the occurrence of DDT in the fatty tissues of Adélie penguins and crabeater seals. Since then pesticide residues have been reported in chinstrap penguins, Wilson storm petrels, snow petrels, giant petrels, and skuas. The detection of DDT and other chlorinated hydrocarbon pesticides in these antarctic organisms furnished the first evidence of the global dispersal of this class of persistent pollutants. It is interesting to note that pesticides have not been found in emperor penguins, which may suggest that those birds and seals that are more or less confined to the Antarctic are likely to have lower levels of contamination than those spending part of their life away from the continent. However, pollutants recognize no national boundaries or territorial seas and are transported from their place of origin to the marine environment via the atmosphere, water movements, and migrating organisms (Figure 5).

In 1972 investigators on board the *Glomar Challenger* found traces of ethane, methane, and ethylene on the continental shelf of Antarctica, predicting the possibility of striking oil and natural gas. This is ominous news, since the drilling for oil and gas and the attendant problem of oil spillage would make the Antarctic, because of the movement of its water masses, a major source of pollution for the three major oceans.

Exploitation of Krill and Other Living Resources

Although "for many decades Antarctic exploration has been falsely represented as an expensive luxury yielding no return except heroism, obscure scientific data, and endearing pictures of penguins" (Holdgate, 1970), it was the phenomenal abundance of antarctic mammals that attracted many economic interests to the region. Now, with the catastrophic decline of the baleen whales during the past forty years, and with the burgeoning of the human population and its increased demand for animal protein, there is great interest in harvesting the only living resource of sizable magnitude left in the Antarctic Ocean.

The existence of large amounts of krill in the Antarctic has been known for many years, but interest in their commercial exploitation arose in the mid-1960s, at a time when the baleen whale stocks had greatly declined due to overharvesting. Pressure to exploit the krill is increasing, since in recent years the stocks of more familiar fishes taken in traditional waters have been overfished or are polluted. Recent declines in the North Atlantic herring fishery, Peruvian anchovies, and Gulf of Mexico shrimp, together with the now defunct California sardine fishery, have sharpened peoples' focus on virtually untouched krill stocks. The reduction in whale populations as a result of commercial whaling would seem to indicate a current surplus of krill, estimated at about 150 million metric tons, which is more than double the annual total world catch of fish (65 million metric tons). As stated before, there is little firm evidence of such a surplus.

Recent Soviet publications indicate that standing stocks of krill are on the order of 800 million to 5 billion metric tons; they predict that 100 million tons could be taken without depleting these stocks. However, several investigators disagree with the high estimates of the Russian scientists and suggest a standing stock of anywhere between 150 million and 1 billion tons. It is these kinds of estimates that are now attracting the attention of such countries such as U.S.S.R., Japan, U.K., Germany, Norway, and Taiwan, to name a few, to look into the possibilities of harvesting the krill. Of these countries, only U.S.S.R. and Japan are catching krill; in 1974 the former took an estimated 200,000 tons, the latter only about 650 tons.

The effect of man's potential harvest of krill now poses a serious problem that, sooner or later, must be faced. As discussed above, krill is the food not only of baleen whales; many other antarctic organisms depend almost entirely on it. What will happen to these organisms if man harvests 100, or even 50, million tons cannot be guessed. Another aspect of the problem is deciding whether to develop the technology to harvest the 100 million tons of krill, or to continue the present annual catch of 1.7 million tons of whales. One strategy is to allow existing whale stocks to recover and then harvest them, rather than attempting to take krill directly. It has also been suggested that with good management it may be possible to take both the 100 million tons of krill *and* the 1.7 million tons of whales.

Future Research

It is clear from what has been said that we do not have the answers to the questions raised above. However, we do know that if krill stocks are to be exploited wisely, we should have realistic data on the density, dimensions, frequency, and distributions of its swarms. One is mindful of the tragedies that have befallen the California sardines, Peruvian anchovies, and antarctic baleen whales; all are testimonies to poor management of natural resources. Unwise or reckless exploitation of antarctic krill could lead to the collapse of their populations and

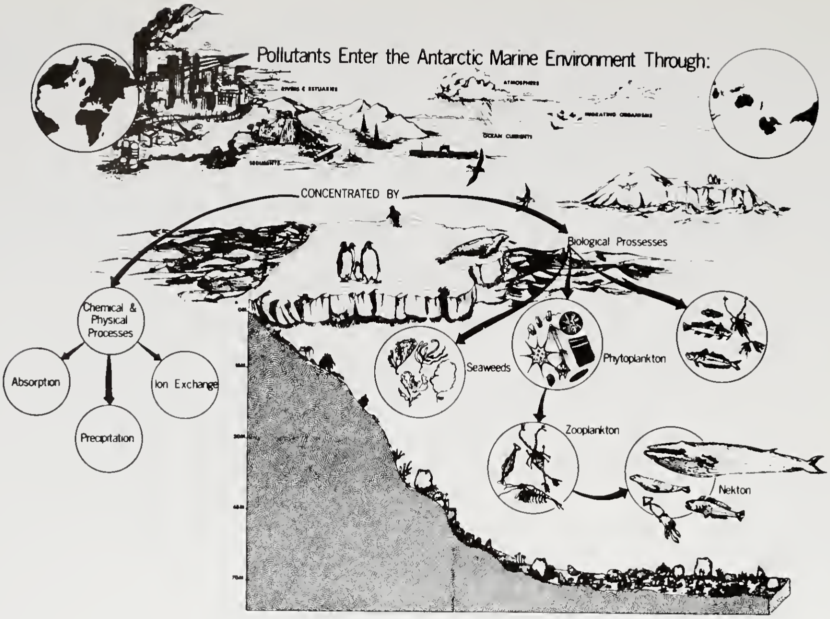


Figure 5. Sources of pollution in the Antarctic. (After El-Sayed, 1972)

trigger disastrous changes throughout the antarctic marine ecosystem.

Interest in conserving antarctic marine resources and in keeping the southern circumpolar waters uncontaminated (or at least much less polluted than northern waters) is evidenced by current studies of the marine ecosystem. For although we have a fairly good knowledge of the composition, abundance, and distribution of the main components of that ecosystem, we still lack information about the relationship between the trophic levels and the flow of energy through it. In short, we do not know how the system works and how it would respond to the stressful problems of pollution and overexploitation of its key organisms.

Efforts by several U.S. scientists to organize multidisciplinary expeditions to study some aspects of the structure and function of the antarctic marine ecosystem resulted in two cruises on U.S.N.S. *Eltanin* in 1970 and 1972, during which investigators undertook a well-balanced program in biological oceanography to study, for example, solar radiation, hydrography, nutrient chemistry, primary productivity, zooplankton, marine fungi, lipid metabolism, and heterotrophic bacteria (Figure 6). Valuable, but limited, data were obtained, and we are still a long way from coming to grips with the central problems. Unfortunately, biological oceanographic investigations have been severely curtailed in recent years, at a time when research efforts should be intensified, not cut back.

Concern for resources led the Scientific Committee on Antarctic Research (SCAR) to establish a Subcommittee on the Marine Living Resources of the Southern Ocean, made up of experts from SCAR nations, as well as from FAO and UNESCO. The subcommittee held its first meeting in May 1974 at McGill University, and its recommendations were subsequently endorsed by the Intergovernmental Oceanographic Commission (IOC) at a meeting held two months later in Buenos Aires. One such recommendation drew attention to the urgent need for a coordinated program in biological oceanography and called for an International Biological Investigation of the Southern Ocean (IBISO). The implementation of IBISO is an important goal of the scientific community. However, such studies need generous financial support from various governments and international organizations.

It has been 50 years since the *Discovery* investigations of antarctic whales—studies that eventually led to an intensive program of physical, chemical, and biological oceanography in the Southern Ocean. One would hope that IBISO will follow the tradition of *Discovery* by adding to our knowledge of the Southern Ocean and by collecting the data needed to develop guidelines for the wise and effective management of its living resources.

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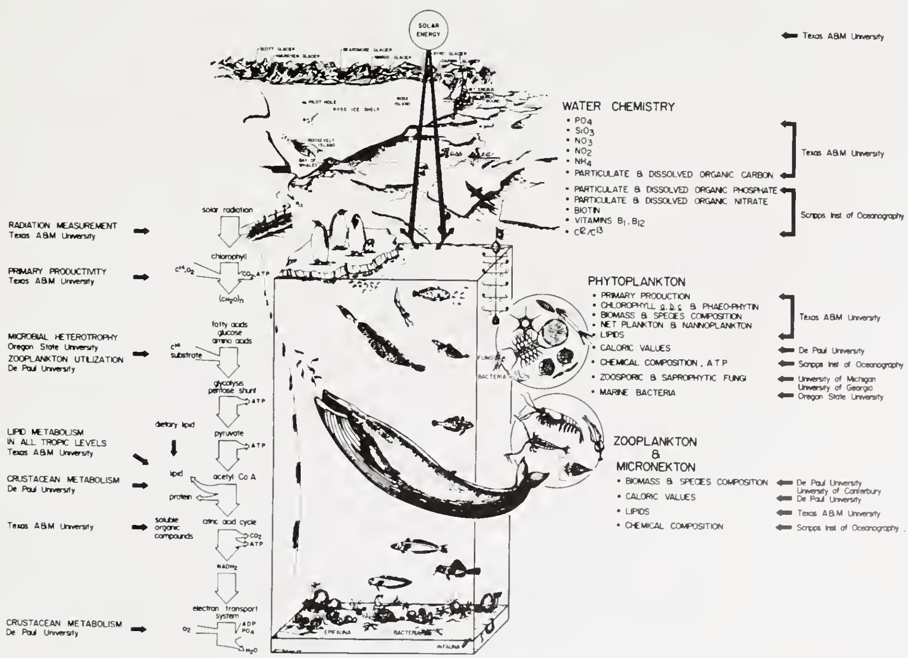

Figure 6. Aspects of the structure and function of the antarctic ecosystem as studied during Eltanin *Cruise 51. (After El-Sayed, 1973)*

A SEA OF

Eroded iceberg off the coast of Wilkes Land. (A. W. Erickson)

Although scarcely defined, the Southern Ocean may be said to begin (as one travels southward) with the encounter of the westerly winds of the roaring forties, south of 40° south latitude. Here the mariner must begin to exercise the special care requisite to survival in the Antarctic. Here, too, political hazards increase. Individuals who work in the Antarctic and those who affect the region from a desk or a conference room elsewhere do equally well to prepare for its political environment, for it is easily perturbed. It is a sea of sensitivities.

No neat set of statutes governs the Southern Ocean. North of 60° S the Southern Ocean is subject to the jurisdictional tugging and hauling that has characterized fishing wars, coastal-state jealousies, unilateral territorial assertions by some states into what others have regarded as the common sea, and other issues that have occupied law-of-the-sea negotiators. One of the issues is ocean-bottom resources; some of the world's most expansive (and juicy, in terms of oil and gas potential) continental shelves sit in northern portions of the Southern Ocean. Here occasional territorial rivalries and resentments linger. The U.S. deep-sea-drilling research vessel *Glomar Challenger* has encountered coastal-state suspicion. Argentine popular sentiment against the continuing British presence in the Falkland Islands is apparent. From 60° S on south the situation is more complicated.

The 60th South Parallel, which runs through open ocean, is the Antarctic Treaty borderline. It delimits a unique international accommodation, in a combination of geographical and political circumstances found nowhere else. Some of the national concerns in evidence in the roaring forties are in evidence also in the treaty area, however, and questions are arising that suggest the treaty relationship needs understanding and cherishing.

Although the treaty emphasizes science as one of its principal purposes and although the effect has been the maintenance of Antarctica as a scientific preserve, the treaty must be recognized for what it is. It is not a science charter. It is the embodiment of a political relationship that the signatories found mutually acceptable (that is, preferable to the alternatives then foreseen) for the South Polar region. That political relationship and its benefits

SENSITIVITIES

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could, but need not, give way—perhaps to heedless and possibly vain greed.

Law is not a simple codification of rules. The meaning of the Antarctic Treaty, obligations and conduct thereunder, and its strengths and weaknesses emerge from the history of political relationships against the background of a geography so hostile that few people other than scientists and explorers have wanted to spend much time there.

At the time of the treaty's writing, in 1959, Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom each claimed chunks of the antarctic region. The claims were in the form of sector assertions—presumptive claims to whatever might be found in spherical triangles reaching to the pole from points in contiguous known, and presumably clearly owned, territories—although the sector principle was unsupported by general recognition, international settlement, or legal precedent. Argentine, Chilean, and U.K. claims overlapped significantly. The United States, which had been among the most active nations in antarctic exploration and science and which air-dropped U.S. flags on the continent, maintained that despite historic U.S. interests there Antarctica was *terra nullius;* the U.S. view seemed to be that Antarctica was owned by no nation and was unownable except under elaborate procedures of qualification in fact and in international legal process that the U.S. believed probably inapplicable to Antarctica anyway. In 1948, discussion of an antarctic trusteeship and then a U.S. proposal to establish an antarctic condominium had failed to win acceptance among claimant states but did elicit a Soviet reminder of historic Russian interest, viz. the Bellingshausen expedition of 1819-21.

Antarctic history was largely but not wholly free of transnational territorial violence—involving, for example, whalers and sealers in the early nineteenth century and British meteorologists and Argentine sailors in 1952. The United Kingdom took its antarctic territorial dispute with Argentina and Chile to the International Court of Justice in 1955, but in 1956 the court noted that neither Argentina nor Chile accepted its jurisdiction in the matter and it declined to rule.

The Antarctic Treaty, entered into force in June 1961, sets none of this history aside; rather, it obligates the parties not to act on it.* The agreement sets forth in treaty law what had been the customary law of the Antarctic during the remarkable international scientific cooperation of the 1957-58 International Geophysical Year; by gentlemen's agreement the countries whose scientists pursued knowledge in the Antarctic refrained from touching claims issues. The treaty provides in pertinent part:

> . . . Nothing contained in the present Treaty shall be interpreted as: (a) a renunciation by any Contracting Party of previously asserted rights of or claims to territorial sovereignty in Antarctica; (b) a renunciation or diminution by any Contracting Party of any basis of claim to territorial sovereignty in Antarctica which it may have whether as a result of its activities or those of its nationals in Antarctica, or otherwise; (c) prejudicing the position of any Contracting Party as regards its recognition or non-recognition of any other State's right of or claim or basis of claim to territorial sovereignty in Antarctica.
>
> . . . No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.

Under the treaty, claims are not to be asserted, enhanced, or derogated. Some antarctic installations are situated purposely in what their countries deem their own territory. Placards at some facilities declare the equivalent of "Our Antarctica." National flags fly. Antarctic installations continue to be owned by national governments. But claims are not resolved. Under the treaty, claims not only are unpressed; they are unacknowledged. Yet in this peculiar accommodation, it is as erroneous to deny as to assert legitimacy of a claim. In crude terms, it is accommodation by nonsettlement; it is an agreement to defer ownership questions indefinitely.

The agreement provides further that "Antarctica shall be used for peaceful purposes only." Within the treaty area, weapons tests, nuclear explosions, radioactive-waste disposal, military maneuvers and training, and "any measures of a military nature" are banned. The treaty provides for dispute settlement by negotiation, mediation, conciliation arbitration, or ultimately, the International Court of Justice; and it established an antarctic consultative mechanism (whose recommendations become antarctic law if unanimously accepted by the consultative parties)

*Antarctic Treaty signatories: Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, Republic of South Africa, Union of Soviet Socialist Republics, United Kingdom of Great Britain and Northern Ireland, United States of America; accessions (subsequent signatories): Brazil, Czechoslovakia, Denmark, German Democratic Republic, Netherlands, Poland, Romania.

for signatory governments active in the treaty area. The treaty is expressly consistent with "the purposes and principles embodied in the Charter of the United Nations," which encourages "regional arrangements or agencies for dealing with such matters relating to the maintenance of international peace and security as are appropriate for regional action. . . . " A break in the treaty structure or an external challenge to it therefore would be a matter of U.N. Security Council concern.

The treaty countries thus agree to comport themselves without offense, to encourage international cooperation in antarctic science, "to exert appropriate efforts" consistent with the U.N. Charter "to the end that no one engages in any activity in Antarctica contrary to the principles or purposes" of the Antarctic Treaty, and to follow certain procedural protocols in an important but inhospitable region, as follows:

The provisions of the present Treaty shall apply to the area south of 60° South Latitude, including all ice shelves, but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area.

The arrangement works. But there are questions, and some go to the heart of the Antarctic Treaty relationship. They can be answered without damage to the relationship, if its delicacy and its effectiveness to date in maintenance of international peace and security in the region are appreciated and if the consequences of its disruption are understood.

There is a trick to accomplishing something in this regime. The key is to win agreement on a purpose or goal while avoiding any action that would touch issues of ownership or that would persuade any country that its options were being foreclosed. Not-quite-formal understandings, of a non-challenging nature, have been used with extraordinary success. Conservation questions afford the best example.

The Scientific Committee on Antarctic Research (SCAR), of the International Council of Scientific Unions, recommended that the Antarctic Treaty consultative parties adopt certain conservation measures. The consultative machinery proposed to its several governments a set of "Agreed Measures for Conservation of Antarctic Flora and Fauna." The "Agreed Measures" provide for Specially Protected Areas, on antarctic lands, that because of distinctive and easily disturbed ecosystems are to be sheltered from human intrusion, with entry only by permit for specified scientific purposes. The consultative meetings, acting on advice from SCAR, have recommended that various sites be designated as Specially Protected Areas. The consultative governments have unanimously approved neither the "Agreed Measures" nor the designations of protected areas. Even so, for the most part, antarctic scientific expeditions act as if the "Agreed Measures" are agreed upon and as if the Specially Protected Areas are especially protected. Recently, taking account of the scientific importance of some ecologically undistinguished sites, the consultative parties have considered designating Sites of Special Scientific Interest. SCAR was asked for its opinion, which was favorable and which presumably has been communicated to committee members' governments by now. It isn't law, however. If the Specially Protected Areas experience is a good predictor, it is not likely to become law.

This experience now may be repeated for portions of antarctic seas. At the thirteenth SCAR meeting, in 1974 at Jackson Hole, Wyoming, the committee's Biology Working Group suggested the establishment of Specially Protected Marine Areas and Marine Sites of Special Scientific Interest. These would be wet analogues of the special areas and sites proposed on land and generally respected but not yet sealed in statute. Here there are added problems. An attempt to establish marine reservations raises questions of the powers of any state or group of states to put boundaries (even for noble purpose) around portions of the sea, whether or not inshore areas are involved. Nevertheless, antarctic expeditions are not precluded from paying the idea some deference and respecting proposed special sites. Emerging consensus in the antarctic international scientific community that a designated marine area ought not be disturbed is likely to be sufficient guidance for marine scientists.

Just sailing in the treaty area can be politically nettlesome. Here again it is useful to appreciate the relationship embodied in the treaty, which requires that each signatory notify all others of "all expeditions to and within Antarctica, on the part of its ships or nationals, and all expeditions to Antarctica organized in or proceeding from its territory." One purpose of the obligation is to give the involved parties the chance to sensitize themselves to each other's concerns respecting the Antarctic and to avoid voluntarily any action whose consequences, perceived in light of those sensitivities, would threaten the treaty relationship. Ideally, everything in Antarctica of political significance as well as of scientific significance is supposed to happen in plain sight.

Notification of scientific expeditions to and in the treaty area for the United States is given routinely by the U.S. government to the other signatories. The U.S. also makes efforts to report tourist expeditions.

Unfortunately, notification is not a simple matter. Many countries—the U.S. among them—do not require sailing plans from their ships or their nationals and may be constitutionally proscribed from doing so. Routine notices to airmen and notices to mariners calling for information on movements to the Antarctic would amount to good-faith effort to meet the treaty provision.

This situation is likely to become more difficult if oil exploration nears the treaty area. Fortunately for the treaty relationship, the largest continental shelves in the Southern Ocean are well north of the 60th South Parallel, and no shelf crosses the line. If 188-nautical-mile-wide resource zones beyond 12-mile territorial seas are confirmed as the law of the sea, no such zone drawn from outside the treaty area will cross the line, with one possible exception—depending on ultimate law-of-the-sea agreements on islands. Such a zone drawn from the British-held South Sandwich Islands would cross 60°S, but in practical terms that would not mean much, considering the lack of shelf surrounding the Sandwich group.

Still, a nervousness obtains in this political relationship, which is the reason for the notification requirement. The treaty works so long as no country tries to undercut it. Crude oil is not the best political lubricant, and in the oil business things tend to be mysterious and complex. How complex is shown in the following example (a true story, with only the names changed to minimize perturbation of the antarctic political environment).

An oil-exploration workboat is docked in Country X, an Antarctic Treaty signatory that has contracted for its services, and dockside rumors—falsely, it later appears—say it is bound for the Weddell Sea. The Weddell Sea is within the treaty area, and a workboat is not the fishing boat, whaler, or passing vessel that the Antarctic Treaty authors had in mind when affirming that the agreement would not prejudice or supersede rights under international law "with regard to the high seas" in the treaty area. The workboat is owned by a corporation in another Antarctic Treaty signatory, Country Y, whose flag it flies, and is leased to and operated by another corporation in Country Y. The operating corporation is a subsidiary of another corporation in Country Y, and that parent corporation is owned by three other corporations in Country Y. Neither Country X nor Country Y informs each other or the several Antarctic Treaty signatories of a workboat excursion in the Weddell Sea, although the notification burden would rest on both Country X and Country Y if the boat actually were going there. Because of the ways in which the industry operates, Country Y in this example might have no prior knowledge of the sailing.

Rumors like that get checked. There is concern in the antarctic community—given the world's intense quest for resources and the cloudy nature of the treaty—that some party may decide to act alone and attempt mineral ventures in the treaty area. To protect the treaty relationship, the signatories may find it necessary to establish informal means for exchange of information on activities in the vicinity of the treaty area.

Questions of exploitation of antarctic resources are troubling, and the problem has come before Antarctic Treaty consultative meetings for discussion. The treaty is silent on exploitation. Within the treaty framework and the political accommodation it represents, questions of ownership of resources cannot be settled.

There is some useful precedent, involving living resources of the Antarctic. Shunning questions of ownership, the treaty consultative machinery developed a separate Convention on Conservation of Antarctic Seals, now circulating among governments for ratification. That precedent may serve in consideration of protection of antarctic krill from overexploitation. Separate international conventions govern whaling; their effectiveness continues to be debated, but their existence demonstrates that some sort of protective regime is possible without threatening the treaty relationship.

Unless accommodations are reached, mineral resources are the more likely source of future frictions. Because the Antarctic is fabled as a storehouse of riches, it is useful to examine whether the fable is founded in enough fact to justify challenges to the treaty relationship. N. A. Wright and P. L. Williams, in *Mineral Resources of Antarctica* (U.S. Geological Survey Circular 705, 1974), offer a summary appraisal:

> . . . Antarctica now has no known economically recoverable resources of any category, nor does Antarctica have any known mineral districts. The few localities where valuable minerals have been identified must be classified as mineral occurrences; that is, occurrences of minerals that could constitute a resource if present in sufficient quantity but that have not been studied adequately to determine quantity. These occurrences would rate even lower than submarginal . . . in degree of

economic feasibility. . . . Present market conditions, as well as quality and location of the coal, indicate that it is not now possible for the coal resources to be considered economically usable; the identified coal and water are definitely submarginal. . . . Another example of mineral occurrence is the appearance of gas in a single drill hole, which was immediately capped. Favorable host rocks, favorable structures, and a first "smell" of gas do not constitute an identified resource; rather the gas is a proved mineral occurrence that supports estimates of the speculative resource potential for gas and oil. All mineral occurrences in Antarctica should be considered in this same context.

The resources of Antarctica are almost exclusively in the category of speculative resources. . . .

Wright and Williams say that "Antarctica seems to have some petroleum potential, but lack of information precludes any real appraisal." It appears from their analysis that the most likely antarctic oil areas are continental shelves. While large-number antarctic oil estimates are discussed from time to time, the Wright-Williams paper fails to confirm them. There is nothing secretive about this. The records of U.S. geology in Antarctica are in the international scientific community's appropriate world data centers.

Oil estimates do change, and the absence of definitively bright prospects of petroleum in antarctic shelves does not alter the political importance of even the merest prospect (see page 30). Unhappily, the Antarctic Treaty is silent on the subject of shelves, except for its enclosure of the area from 60°S on south with due allowance for right of innocent passage and navigation.

It appears to be within the authority of the Antarctic Treaty powers in this matter, too, to achieve an accommodation consistent with the political relationship embodied in the treaty. The matter of ownership of mineral resources need not be raised, but environmental-control machinery could be established and made applicable to the treaty area. If there is exploitable antarctic oil, if it can be exploited safely, and if the antarctic powers feel compelled to accept its exploitation, they may find that preferable to pressing the matter of resource ownership is an ad hoc arrangement to avoid it—by simply reserving all rights and licensing an appropriate U.N. authority, perhaps the evolving international seabed authority, to handle the matter so long as the Antarctic Treaty countries so agree; oil profits could be distributed according to the formulas developed by the international community for operation of the seabed authority. This is a highly speculative way out, of course, but it is one possibility by which the problem can be handled without damage to the treaty relationship. It is a possibility that could apply as well to any deep-sea mining in the treaty area.

It is conceivable that conflicts of law will arise between the Antarctic Treaty and the law-of-the-sea treaty now under negotiation. Such conflicts can be resolved, case by case, in the International Court of Justice.

The Antarctic Treaty can but need not be opened for renegotiation and for unilateral withdrawal in 1991. One or more of the signatories may renounce it unilaterally or simply act as if it does not exist. However, the treaty and its overall political framework have some strong points. Withdrawal or wholesale violation would involve the offender in lengthy international diplomatic and legal dispute. An unilateral withdrawal probably would be pointless. A country unilaterally renouncing the treaty in order to get mineral resources would find itself without the clear property-title that financial institutions all over the world require before financing the large investment needed for mineral exploration and exploitation.

The treaty relationship is delicate, but it does work. It faces problems—some procedural, some really threatening—that call for imaginative solutions consistent with the treaty language and the political relationships encompassed in that language. With all its ambiguities, the existing antarctic legal regime is best left alone, save for steps the treaty powers may deem essential to permit demonstrably necessary economic exploitation subject to firm, appropriate environmental controls.

Science is becoming more aware of the Antarctic's importance in global processes—for example, in the shaping of world climate (see page 16) and in the generation of nutrients for fisheries far to the north—and environmental controls will be needed in the Antarctic to protect these processes from destructive perturbation (see pages 38 and 45). Although national rivalries cross the 60th South Parallel, at least south of 60°S the Southern Ocean powers have behaved themselves. The world has an investment in that treaty relationship.

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